



DESIGN FOR DISCOVERY: CULTIVATING QUANTUM PHYSICS CREATIVITY THROUGH AN INTEGRATED COGNITIVE LOAD AND PSYCHOLOGICAL SAFETY E-MODULE

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ABSTRACT

Aim/Purpose

This study aims to propose, implement, and evaluate an integrated pedagogical framework, Design for Discovery, embedded within an interactive e-module. The study addresses the pedagogical paradox in quantum physics education, where rigorous conceptual demands often limit opportunities for creative exploration.

Background

Quantum physics education presents a dual challenge: achieving deep conceptual understanding while fostering scientific creativity. Traditional instruction often imposes a high cognitive load, limiting students' capacity for higher-order thinking. This study proposes that technology-enhanced environments can address this by integrating three mechanisms: cognitive headroom, psychological safety, and epistemic curiosity.

Methodology

This study employed an embedded mixed-methods case study design involving 25 third-year physics education students at Universitas Jambi, Indonesia. Quantitative data were collected using the Scientific Creative Thinking Skills Test (SCTST) and a conceptual understanding test, while qualitative data were obtained through a reflexive perception survey. The intervention consisted of a five-week implementation of an interactive e-module incorporating visualization, sandbox simulations, and private feedback.

Contribution

This study contributes by proposing the Design for Discovery Framework, which conceptualizes creativity as an emergent outcome of the interaction

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	among cognitive, affective, and motivational mechanisms. The framework provides both a theoretical model and a practical design blueprint for developing creativity-supportive learning environments in complex STEM domains.
Findings	The results indicate statistically significant improvements in both scientific creative thinking ($t(24) = 5.89, p < .001, d = 1.18$) and conceptual understanding ($t(24) = 7.12, p < .001, d = 1.42$). Qualitative analysis identified three key mechanisms: (1) cognitive headroom enabled by visualization, (2) epistemic curiosity triggered through sandbox exploration, and (3) psychological safety facilitated by private feedback. These findings suggest that learning outcomes, including both creative thinking and conceptual understanding, emerge from the interaction of cognitive, affective, and motivational processes.
Recommendations for Practitioners	Instructional designers should move beyond content delivery and focus on engineering cognitive learning environments. This includes integrating visualization to reduce cognitive load, incorporating sandbox features to promote exploration, and providing private feedback to support psychological safety and risk-taking.
Recommendations for Researchers	Future research should examine the generalizability of the framework across different STEM disciplines and cultural contexts. Further studies may also explore real-time measurement of cognitive load and psychological safety using learning analytics or physiological data.
Impact on Society	This study provides a scalable model for fostering creativity within rigorous scientific education, contributing to the development of a STEM workforce capable of both deep expertise and innovative problem-solving.
Future Research	Future work may extend this framework through multi-institutional studies and the integration of adaptive or AI-driven learning systems, further to personalize cognitive and affective support in complex learning environments.
Keywords	cognitive headroom, quantum physics, cognitive load theory, psychological safety, e-module, STEM education

INTRODUCTION

The landscape of modern higher education, particularly within the Science, Technology, Engineering, and Mathematics (STEM) disciplines, is currently navigating a profound and persistent pedagogical paradox. On one side of the educational equation lies the absolute necessity for rigorous, deep conceptual understanding. Disciplines, such as physics, and specifically quantum mechanics, demand a level of cognitive precision and procedural fluency that leaves little margin for error. On the other side of this equation is the burgeoning demand for a workforce capable of 21st-century skills, most notably, creativity, critical thinking, and complex problem-solving.

The paradox emerges because the instructional strategies historically employed to achieve the first objective (rigour and mastery) often inadvertently suppress the conditions necessary to achieve the second (creativity and risk-taking). In the pursuit of cognitive efficiency and standardized procedural competence, curricula often become dense and prescriptive, leaving scant room for the messy, divergent, and often inefficient process of creative exploration.

This tension is nowhere more palpable than in the teaching of quantum physics. As a domain, quantum physics is notoriously abstract, counterintuitive, and mathematically dense. Concepts such as wave-particle duality, superposition, and entanglement fundamentally challenge the classical intuitions that students have developed throughout their lives (Bitzenbauer, 2021; Marshman &

Singh, 2015). Consequently, the cognitive load imposed on learners is intrinsically high. When educators attempt to navigate this complex terrain using traditional lecture-based or static text-based methods, the cognitive bandwidth of students is often entirely consumed by the struggle to merely comprehend the material, leaving no residual mental capacity – or “cognitive headroom” – for creative thought, questioning, or hypothesis generation. Furthermore, the historical culture of physics education, which often valorizes the “single correct answer” and penalizes error, can create an environment of high evaluation apprehension. In such environments, psychological safety is compromised; students retreat into safe, convergent thinking strategies to avoid the social and academic costs of making mistakes, thereby effectively shutting down the neural and psychological pathways required for originality and innovation.

This research addresses this critical gap by proposing and evaluating a novel pedagogical framework titled “Design for Discovery.” We posit that the perceived dichotomy between rigorous content mastery and creative skill development is a false one, sustained by outdated instructional designs that fail to account for the learner’s holistic cognitive-affective architecture. By leveraging the affordances of modern Information Technology (IT) – specifically, interactive e-modules – we argue that it is possible to engineer learning environments that simultaneously optimize cognitive load, foster psychological safety, and trigger epistemic curiosity.

The “Design for Discovery” framework suggests that technology-enhanced learning environments can cultivate creativity by synergizing three distinct but interconnected mechanisms. First, by rigorously applying Cognitive Load Theory (CLT) principles, such as the coherence, signaling, and segmentation effects, instructional design can minimize extraneous load. This reduction does not merely make learning “easier”; it strategically frees up finite working memory resources, creating a reservoir of mental capacity we term “cognitive headroom.” Second, this freed capacity must be directed toward productive exploration. We propose that *epistemic curiosity* (the intrinsic desire to close information gaps and understand underlying mechanisms) serves as the vector for this energy. Finally, for this curiosity to manifest as creative behavior (experimentation, questioning, divergent hypothesis generation), the environment must be *psychologically safe*. Students must feel that the “cost” of exploration is low, and that failure is a productive step in the learning process rather than a signal of incompetence.

However, existing studies have not systematically integrated cognitive load optimization, psychological safety, and epistemic curiosity into a unified instructional design framework to foster scientific creativity in quantum physics learning. This gap highlights the need for a comprehensive approach that not only enhances learning efficiency but also actively supports creative exploration in cognitively demanding domains. In doing so, this study moves beyond evaluating an instructional intervention to advance a theoretically grounded framework for designing creativity-supportive learning environments in complex STEM domains.

To test this framework, we developed an interactive e-module for a “Modern Quantum Physics” course and implemented it within a physics education program at Universitas Jambi. This study employs an embedded mixed-methods case study design to answer three pivotal research questions:

- Is there a statistically significant difference in students’ creative thinking skills in quantum physics before and after the implementation of the “Design for Discovery” e-module?
- Is there a statistically significant difference in students’ conceptual understanding before and after the intervention?
- How do the specific design features of the e-module (sandbox simulations, visualization, and private feedback) interact to foster cognitive headroom, trigger epistemic curiosity, and ensure psychological safety from the students’ perspective?

By answering these questions, this report aims to provide a robust, empirically validated blueprint for educators and instructional designers seeking to resolve the tension between rigour and creativity in STEM education. To theoretically ground this proposed framework, the following section reviews key

constructs underpinning the Design for Discovery approach, namely scientific creative thinking, cognitive load theory, psychological safety, and epistemic curiosity.

LITERATURE REVIEW

SCIENTIFIC CREATIVE THINKING IN PHYSICS EDUCATION

Scientific creative thinking has increasingly been recognized as a critical competency in STEM education, particularly in domains characterized by high abstraction, such as quantum physics (Whitehorn et al., 2025). Recent literature conceptualizes scientific creativity as a multidimensional construct encompassing fluency, flexibility, originality, and elaboration, often extended with inquiry orientation and contextual sensitivity (Firdaus et al., 2025; Puspita et al., 2025). Despite this growing consensus, the field continues to face challenges in establishing clear operational definitions, as creative thinking often overlaps with critical thinking and problem-solving.

In physics education, domain-specific creativity requires not only the generation of novel ideas but also the ability to meaningfully interpret abstract phenomena and translate them into scientifically plausible representations. This necessitates assessment approaches that are sensitive to disciplinary context. Recent advances in creativity assessment, including Rasch-modeled instruments and domain-adapted frameworks, emphasize the importance of aligning measurement tools with both cognitive processes and disciplinary knowledge structures (Benedek & Beaty, 2025; Xu et al., 2026).

In response to these developments, this study adopts a domain-specific operationalization of scientific creative thinking, focusing on four core dimensions: fluency, flexibility, originality, and elaboration. These dimensions are consistent with the Torrance tradition of creativity research while being explicitly contextualized within quantum physics problem spaces. The Scientific Creative Thinking Skills Test (SCTST) used in this study is therefore conceptualized as an adaptation of established creativity frameworks, redesigned to capture the unique epistemic demands of physics reasoning.

Importantly, prior research demonstrates that digital and simulation-based pedagogies can significantly enhance these dimensions of creativity by enabling iterative experimentation, visualization, and exploratory reasoning (Habibi et al., 2020; Skakov et al., 2025). However, these studies often treat creativity as an outcome without fully theorizing the underlying cognitive and affective mechanisms that enable it. This gap highlights the need for an integrated framework that explains not only whether creativity improves, but how and why it emerges within complex learning environments.

COGNITIVE LOAD THEORY AND THE CONCEPT OF COGNITIVE HEADROOM

Cognitive Load Theory (CLT) provides a foundational lens for understanding learning in cognitively demanding domains such as quantum physics. Traditional CLT distinguishes between intrinsic, extraneous, and germane cognitive load, emphasizing the importance of minimizing extraneous load to optimize learning (Sweller, 2024), a distinction increasingly supported by precise neurophysiological measurements and brain-wave analyses (C.-C. Wang et al., 2022; Xiao et al., 2025). However, recent developments extend this perspective by positioning cognitive load not merely as a constraint, but as a design variable that can be strategically managed to enable higher-order thinking (Feldon et al., 2024; Hanham et al., 2023).

In this expanded view, reducing extraneous load does not simply facilitate comprehension; it creates what can be termed cognitive headroom, a surplus of working memory resources that can be allocated to complex processes such as hypothesis generation, conceptual integration, and creative reasoning. Instructional strategies grounded in multimedia learning principles, such as segmentation, signaling, and coherence, have been shown to reduce extraneous load and improve cognitive efficiency effectively (Castro-Alonso et al., 2021; Noetel et al., 2022).

However, emerging research also demonstrates that cognitive load is not purely cognitive; it is dynamically intertwined with affective states such as anxiety, engagement, and emotional regulation (Brockbank & Feldon, 2024; Young et al., 2021). This suggests that optimizing cognitive load alone is insufficient. Without addressing the learner's affective experience, the cognitive resources freed through instructional design may not be effectively utilized for creative processes. Thus, while CLT provides the capacity for creativity through cognitive headroom, it does not by itself explain how that capacity is activated or sustained. This limitation underscores the need to integrate CLT with affective and motivational constructs.

PSYCHOLOGICAL SAFETY AS A COGNITIVE-AFFECTIVE REGULATOR

Psychological safety, defined as the perception that one can take intellectual risks without fear of negative consequences, plays a critical role in mediating the relationship between cognitive resources and creative performance. In high-stakes STEM environments, fear of failure and evaluation apprehension can impose significant extraneous cognitive load, diverting attention from learning to self-monitoring, a challenge consistently identified as hindering team effectiveness and productivity in complex engineering design and applied industry environments (Clausen et al., 2025; Cole et al., 2022; Wei & Han, 2025).

Recent studies in digital learning environments demonstrate that psychological safety is closely linked to both cognitive efficiency and conceptual understanding. Supportive, low-risk environments, particularly those facilitated through private feedback and adaptive digital systems, can reduce anxiety and enable learners to engage more deeply with complex tasks (Sarzhanova et al., 2025). Moreover, emotional states have been shown to directly influence cognitive load, with positive or regulated emotional conditions reducing extraneous load and enhancing performance (Jamieson et al., 2022; C. Wang et al., 2025).

From this perspective, psychological safety functions as a cognitive-affective regulator. It ensures that the cognitive headroom created by instructional design is not consumed by anxiety or fear but remains available for exploratory and creative processes. Without such safety, learners are more likely to adopt risk-averse strategies, limiting originality and divergent thinking. Therefore, psychological safety provides not just emotional comfort for learning but also the functional conditions necessary for creativity.

EPISTEMIC CURIOSITY AS THE ACTIVATION MECHANISM

While cognitive headroom provides capacity and psychological safety provides permission, learners still require a motivational driver to engage in creative exploration. This role is fulfilled by epistemic curiosity, defined as the desire to acquire new knowledge and resolve informational gaps.

Contemporary research distinguishes between interest-type curiosity, associated with intrinsic enjoyment and exploratory behavior, and deprivation-type curiosity, associated with the need to resolve uncertainty (S. W.-Y. Lee et al., 2022; Tu & Lee, 2025). In digital and simulation-based learning environments, epistemic curiosity has been shown to significantly enhance engagement, persistence, and deep learning (Cheng, 2023).

Interactive simulations are particularly effective at triggering curiosity by creating immediate, manipulable information gaps. When learners observe unexpected outcomes or patterns in a simulation, they are prompted to ask exploratory questions, which leads to iterative experimentation and hypothesis generation. This process aligns closely with the core dimensions of creativity, particularly fluency and flexibility.

Importantly, curiosity does not operate in isolation. Its effectiveness depends on both cognitive capacity (headroom) and affective conditions (safety). Without sufficient cognitive resources, curiosity may lead to confusion; without psychological safety, it may not be expressed at all. Thus,

epistemic curiosity functions as the activation mechanism that transforms potential (cognitive headroom) into actual creative behavior.

SYNTHESIS: THE DESIGN FOR DISCOVERY FRAMEWORK

Although prior research has extensively examined cognitive load, psychological safety, and epistemic curiosity, these constructs have largely been investigated in isolation. Existing studies grounded in Cognitive Load Theory (CLT) tend to prioritize instructional efficiency, while curiosity-driven approaches emphasize engagement without systematically addressing cognitive constraints. Similarly, research on psychological safety often focuses on collaborative or social learning contexts without explicitly linking it to cognitive processing. This fragmentation has led to a limited understanding of how these mechanisms interact to produce higher-order outcomes, such as creativity, in complex STEM learning environments.

To address this gap, this study proposes an integrated pedagogical model, the Design for Discovery Framework, that conceptualizes creativity as an emergent outcome of the dynamic interaction among cognitive, affective, and motivational mechanisms. Within this framework, cognitive load optimization creates cognitive headroom, thereby providing the mental capacity for higher-order thinking. However, the availability of such capacity alone is insufficient; it must be regulated through psychological safety, which ensures that cognitive resources are not diverted toward anxiety or fear of negative evaluation. In parallel, epistemic curiosity operates as the activating force that directs these available resources toward exploratory and generative cognitive activities.

These theoretical mechanisms are operationalized through specific instructional design features embedded within the e-module. Dynamic visualizations are employed to reduce extraneous cognitive load and support conceptual clarity. At the same time, sandbox simulations are designed to induce epistemic curiosity by allowing learners to explore open-ended parameter spaces and observe emergent patterns. In addition, private feedback systems are implemented to foster psychological safety by minimizing evaluation apprehension and encouraging intellectual risk-taking. Through this alignment, the framework establishes a direct linkage between design features and underlying psychological processes.

As a result of this integration, the framework positions scientific creative thinking – operationalized through fluency, flexibility, originality, and elaboration – as a measurable outcome of a carefully engineered cognitive environment. At the same time, conceptual understanding is not treated as a competing objective but as a co-emergent outcome of the same processes. In this sense, the Design for Discovery Framework advances beyond existing CLT-based e-learning approaches by explicitly modeling the synergistic interaction between cognitive efficiency, affective regulation, and motivational activation, thereby providing both a theoretical contribution and a practical blueprint for designing creativity-supportive learning environments in complex STEM domains.

This framework directly informs the formulation of the research questions. It guides the selection of variables examined in this study, including scientific creative thinking, conceptual understanding, and the underlying learning mechanisms.

METHODOLOGY

RESEARCH DESIGN

Guided by the Design for Discovery Framework, this study employed an embedded mixed-methods case study design to examine both the outcomes and underlying mechanisms of the proposed instructional approach. This design was selected to capture both measurable conceptual understanding and the cognitive–affective–motivational processes that explain how and why these outcomes occur.

The quantitative component utilized a one-group pretest–posttest design to examine changes in students' scientific creative thinking and conceptual understanding following the intervention. The qualitative component was embedded in this design through a reflexive perception survey, enabling an in-depth exploration of students' cognitive, affective, and motivational experiences during their interactions with the e-module.

Recent methodological literature highlights that embedded mixed-methods designs enhance interpretative rigor by integrating numerical outcomes with contextualized explanations, particularly in complex educational settings (Plano Clark et al., 2022; Zhou et al., 2024). This approach enables the generation of meta-inferences, in which qualitative findings are used to explain quantitative trends, thereby strengthening the study's explanatory power.

CONTEXT AND PARTICIPANTS

The study was conducted at Universitas Jambi, Indonesia, within the Physics Education program. The participants comprised the entire cohort of 25 third-year undergraduate students enrolled in the Modern Quantum Physics course.

A purposive sampling strategy was employed because the cohort represents a critical case characterized by prior exposure to foundational physics concepts yet ongoing conceptual challenges in quantum mechanics. Including the entire class ensured ecological validity and eliminated sampling bias within the instructional context.

Although the sample size is relatively small, it is consistent with case study research and is appropriate for detecting large within-subject effects while providing rich qualitative insights. Moreover, the sample size aligns with recommendations for embedded mixed-methods studies, where depth of analysis and contextual richness are prioritized over statistical generalization.

INTERVENTION DESIGN: THE DESIGN FOR DISCOVERY E-MODULE

The intervention consisted of a custom-developed interactive e-module designed according to the Design for Discovery Framework. The module was implemented over five weeks and covered key topics in quantum physics, including blackbody radiation, the photoelectric effect, Compton scattering, wave-particle duality, and Schrödinger's equation.

The instructional design explicitly operationalized the theoretical mechanisms of the framework. Cognitive load was managed through dynamic visualizations and segmented content, reducing extraneous processing demands. Epistemic curiosity was activated through sandbox simulations that allowed students to manipulate parameters and explore emergent patterns. Psychological safety was fostered through private, automated feedback that minimized evaluation apprehension and encouraged intellectual risk-taking.

This alignment between design features and psychological mechanisms ensures that the intervention functions not merely as a content delivery tool but as a structured cognitive environment engineered to support creative thinking.

INSTRUMENTS

Scientific Creative Thinking Skills Test (SCTST)

The Scientific Creative Thinking Skills Test (SCTST) was developed as a domain-specific adaptation of established creativity assessment frameworks, particularly the Torrance Tests of Creative Thinking (TTCT). It was contextualized to align with the epistemic characteristics of quantum physics. Recent methodological research emphasizes that domain-specific adaptation is essential to ensure that creativity assessments capture not only divergent thinking but also the meaningful application of disciplinary knowledge (Acar et al., 2023; H. L. Lee et al., 2025).

The SCTST consisted of open-ended essay tasks designed to elicit creative responses grounded in concepts from quantum physics. Students were required to generate, elaborate, and justify ideas

based on abstract phenomena such as superposition and wave-particle duality. Responses were evaluated across four dimensions of scientific creative thinking, namely fluency, flexibility, originality, and elaboration. Fluency refers to the number of relevant ideas generated; flexibility reflects the diversity of conceptual categories represented in the responses; originality captures the novelty and uniqueness of the ideas; and elaboration indicates the level of detail and depth in the explanation.

To ensure scoring consistency and transparency, a structured analytic rubric was employed. Fluency was assessed by the number of relevant ideas produced, with higher scores assigned to responses that demonstrated more distinct ideas. Flexibility was evaluated by identifying the range of conceptual categories used in the responses, indicating the ability to approach problems from multiple perspectives. Originality was determined by comparing responses across participants, with higher scores awarded to ideas that were uncommon or unexpected within the cohort. Elaboration was assessed based on the clarity, depth, and completeness of the explanation provided for each idea.

Content validity was established through expert review involving two specialists in physics education and one educational psychologist, ensuring alignment between the test items and the targeted constructs. Reliability analysis yielded a Cronbach's alpha coefficient of 0.88, indicating high internal consistency of the instrument.

Conceptual Understanding Test

Conceptual understanding was assessed using a multiple-choice test designed to measure deep conceptual reasoning in quantum physics. The instrument focused on students' ability to interpret physical phenomena and apply conceptual principles rather than perform procedural calculations. This approach aligns with contemporary recommendations in physics education research that emphasize conceptual understanding as a foundation for meaningful learning.

The test demonstrated high internal consistency, with a Cronbach's alpha coefficient of 0.91, indicating that the instrument reliably measures students' conceptual understanding across the targeted domains.

Reflexive Perception Survey

To investigate the mechanisms underlying the observed conceptual understanding, a semi-structured reflexive perception survey was administered at the end of the intervention. The instrument's design was explicitly aligned with the theoretical constructs of the Design for Discovery Framework: cognitive load, psychological safety, and epistemic curiosity.

The survey employed open-ended questions to encourage students to reflect on their learning experiences during interaction with the e-module. Participants were prompted to describe how specific design features influenced their understanding, emotional responses, and exploratory behaviors. For instance, students were asked to reflect on moments when visualizations facilitated comprehension, situations in which they felt comfortable taking intellectual risks, and experiences that sparked curiosity during their interactions with the simulations.

This approach is consistent with reflexive qualitative methodologies, which emphasize participants' subjective experiences to uncover underlying cognitive and affective processes (Braun & Clarke, 2022). The use of open-ended, theory-aligned prompts enabled the collection of rich qualitative data that directly informed the analysis of the mechanisms underlying the intervention's effectiveness.

PROCEDURE

The study was conducted over five weeks. In the first week, pretests measuring creative thinking and conceptual understanding were administered. During weeks two to four, students engaged with the e-module in a blended learning format, combining self-paced exploration with facilitated discussions. The instructor's role was primarily as a facilitator, encouraging exploration rather than direct instruction. In the final week, posttests were administered, followed by the reflexive perception survey.

DATA ANALYSIS

Quantitative data were analyzed using paired-samples t-tests to determine statistically significant differences between pretest and posttest scores. Effect sizes were calculated using Cohen's *d* to assess the magnitude of change.

Qualitative data were analyzed using reflexive thematic analysis following Braun and Clarke's six-phase framework. This approach emphasizes iterative coding, researcher reflexivity, and theoretical alignment, ensuring methodological rigor and transparency (Braun & Clarke, 2022; Byrne, 2022).

The analysis involved familiarization with the data, initial coding, theme generation, theme review, and refinement. To enhance analytical rigor, coding was conducted independently by two researchers, followed by discussion to resolve discrepancies and refine thematic interpretations.

The integration of quantitative and qualitative findings occurred during the interpretation stage, enabling the identification of explanatory mechanisms linking instructional design features to observed creative thinking and conceptual understanding. The results of these analyses are presented in the following section, organized according to quantitative outcomes and qualitative insights aligned with the research questions.

FINDINGS

The results of this study indicate a positive impact of the Design for Discovery framework. The findings are presented in two sections: quantitative outcomes on student performance and qualitative insights explaining the mechanisms underlying these changes.

QUANTITATIVE RESULTS: IMPACT ON CREATIVITY AND CONCEPTUAL UNDERSTANDING

The statistical analysis revealed a robust positive impact of the e-module intervention on both creative thinking skills and conceptual understanding (Table 1). These findings directly address RQ1 and RQ2, demonstrating that implementing the Design for Discovery e-module significantly enhances both scientific creative thinking and conceptual understanding.

Table 1. Comparison of pretest and posttest scores (N=25)

Variable	Time	Mean	Standard deviation	t-value	df	p-value	Effect size (Cohen's <i>d</i>)
Creative thinking skills (SCTST)	Pretest	65.40	8.20	5.89	24	< .001	1.18
	Posttest	78.90	7.50				
Conceptual understanding	Pretest	58.20	9.10	7.12	24	< .001	1.42
	Posttest	81.50	6.80				

Note: Effect sizes are interpreted based on Cohen's (2013) criteria.

Interpretation of Quantitative Data: The analysis indicates a highly significant improvement in both domains ($p < .001$).

- **Creative Thinking:** The mean score rose from 65.40 to 78.90. The effect size $d = 1.18$ is considered “large” in educational research, indicating that the intervention shifted the average student from the 50th to roughly the 88th percentile of the pretest distribution. This suggests that domain-specific creativity can be explicitly supported and improved through intentional instructional design.

- **Conceptual Understanding:** The increase from 58.20 to 81.50 ($d = 1.42$) is even more pronounced. This finding is particularly important as it addresses the common concern that focusing on creativity or exploration may reduce emphasis on content mastery. On the contrary, the data suggest that the deep processing required for creative elaboration reinforces conceptual understanding.

QUALITATIVE RESULTS: UNPACKING THE MECHANISMS

The thematic analysis of student perception data yielded three major themes that explain the underlying mechanisms behind the quantitative results. These themes are closely aligned with the theoretical pillars of the Design for Discovery framework. Together, these themes provide a coherent explanation of the mechanisms underlying the quantitative improvements, thereby offering a comprehensive answer to RQ3.

Theme 1: Creation of “cognitive headroom” via extraneous load reduction

Students consistently reported that the e-module’s design features – specifically the dynamic visualizations and segmented text – reduced the mental effort required to visualize the phenomena. Students explicitly linked this perceived reduction in load to an increased capacity to *think* about the concepts.

Representative Quote: “Before, I could not picture superposition. However, the animation in the module helped me ‘see’ what it meant. The load in my head felt lighter because I did not have to imagine it from scratch, so I could focus more on actually thinking about the concept.” (Participant 7)

This finding provides empirical support for the “Cognitive Headroom” hypothesis: by offloading the visualization task to the e-module (applying the Coherence Principle), the students’ limited working memory was freed. Crucially, they did not just “relax”; they reinvested this freed capacity into germane processing (understanding the concept) and creative elaboration.

Theme 2: Triggering epistemic curiosity through active exploration

The “Sandbox Simulations” were identified as the primary driver of student engagement. Unlike traditional verification labs, where students follow a recipe to confirm a known law, the sandbox environment encouraged open-ended play. This appears to have triggered interest-type epistemic curiosity.

Representative Quote: “The best part was being able to ‘mess with’ the parameters in the wave-particle duality simulation. It made me curious, ‘What happens if I do this?’ I felt like I was discovering the patterns myself, not just being told the formula. It pushed me to try lots of combinations.” (Participant 15)

This response indicates a shift from extrinsic motivation toward intrinsic engagement, which is strongly associated with increased participation in exploratory and generative cognitive processes. The students’ active experimentation reflects the behavioral manifestation of fluency and flexibility, suggesting that curiosity-driven interaction plays a central role in supporting creative thinking.

Theme 3: Psychological safety as an enabler of intellectual risk-taking

The third theme highlights the critical role of the affective environment. Students contrasted the e-module experience with the high-stakes environment of a typical classroom. The privacy of the feedback loop created a psychologically safe zone where errors were depersonalized.

Representative Quote: “I could try a ‘crazy’ answer on the quiz without feeling embarrassed. The feedback helped me understand why my idea was off, which was more helpful than just getting the correct answer. It made me brave enough to try more original approaches to the essay questions.” (Participant 4)

This response illustrates the critical role of psychological safety in enabling intellectual risk-taking. The absence of evaluation-related anxiety appears to encourage students to explore unconventional ideas and adopt more original approaches. This finding supports the interpretation that psychological safety is a necessary condition for the emergence of originality in creative thinking. These findings provide an empirical basis for interpreting how the identified mechanisms interact to produce the observed learning outcomes, particularly improvements in both creative thinking and conceptual understanding.

DISCUSSION

EFFECTS ON SCIENTIFIC CREATIVE THINKING (RQ1)

The findings of this study demonstrate a significant improvement in students' scientific creative thinking following the implementation of the Design for Discovery e-module. Quantitative results indicate increases across all four dimensions – fluency, flexibility, originality, and elaboration – suggesting that the intervention effectively supported both the generation and development of ideas within quantum physics contexts.

This empirical evidence aligns with recent studies showing that digital and simulation-based learning environments can produce moderate-to-large gains in creative thinking in STEM education. For instance, immersive and simulation-based interventions have been reported to yield substantial effect sizes in creativity development, often exceeding conventional instructional approaches (Gui et al., 2023; Irwanto et al., 2025). Similarly, virtual and interactive environments have been shown to facilitate creative processes by enabling iterative exploration and experimentation (Antonio & Castro, 2023).

From an interpretative perspective, these improvements can be understood through the lens of cognitive load optimization. By reducing extraneous cognitive load through structured visualizations and segmented content, the e-module created cognitive headroom, allowing students to engage in higher-order thinking. This interpretation is consistent with prior research demonstrating that effective cognitive load management enhances complex cognitive performance, including creative reasoning (Skulmowski & Xu, 2022).

Moreover, sandbox simulations appear to have played a critical role in fostering divergent thinking. The open-ended nature of these environments enabled students to generate multiple hypotheses and explore alternative representations of quantum phenomena, thereby directly supporting fluency and flexibility. This mechanism is supported by findings that inquiry-based and simulation-driven learning environments promote collaborative exploration and creative idea generation (Fujiani et al., 2023), yielding cognitive benefits comparable to those observed in open-ended, applied engineering laboratories (Mahmoud et al., 2020).

Importantly, the observed gains in originality and elaboration suggest that the intervention did not merely increase the quantity of ideas but also enhanced their quality and depth. This indicates that the learning environment successfully encouraged students to move beyond surface-level responses toward more sophisticated and well-developed conceptualizations. In the context of quantum physics, where abstract reasoning is essential, this represents a meaningful advancement in students' creative scientific thinking.

EFFECTS ON CONCEPTUAL UNDERSTANDING (RQ2)

In addition to improvements in creative thinking, the results indicate a significant increase in students' conceptual understanding of quantum physics. This finding is consistent with a growing body of literature demonstrating that digital and simulation-based learning environments are effective in enhancing conceptual learning, particularly for abstract and non-intuitive scientific concepts.

Empirical studies have shown that virtual laboratories and simulation-based tools can produce learning gains comparable to or exceeding those of traditional laboratory approaches, particularly in resource-limited contexts (Hu et al., 2025; Li & Liang, 2024). These environments allow learners to visualize phenomena that are otherwise invisible, thereby bridging the gap between abstract theory and observable representation.

The findings of this study provide further support for this claim. The use of dynamic visualizations within the e-module enabled students to interact with representations of quantum phenomena, such as wave-particle duality and probabilistic behavior, which are typically difficult to grasp through conventional instruction. This aligns with research indicating that multimodal representations reduce cognitive barriers and facilitate deeper conceptual understanding (Ruamba et al., 2025).

From a theoretical standpoint, the improvement in conceptual understanding can be interpreted as a direct consequence of optimized cognitive load. By minimizing unnecessary processing demands, students were able to allocate more cognitive resources to schema construction and conceptual integration. This is consistent with findings that moderate reductions in cognitive load enhance learning efficiency and knowledge retention (Gierczyk et al., 2025).

Furthermore, the integration of exploratory simulations appears to have facilitated epistemological shifts, encouraging students to move from passive reception of information toward active knowledge construction. Such shifts are particularly important in quantum physics, where understanding requires reconciling counterintuitive concepts with probabilistic reasoning (Justice et al., 2025). Thus, the observed gains in conceptual understanding are not only statistically significant but also pedagogically meaningful.

While these findings demonstrate improved conceptual understanding, they do not fully explain the processes through which these outcomes emerged. To address this, the following section examines the mechanisms underlying the link between instructional design features and observed learning effects.

MECHANISMS UNDERLYING LEARNING EFFECTS (RQ3)

While the qualitative findings identified three dominant experiential themes (cognitive headroom, epistemic curiosity, and psychological safety) these can be interpreted as interacting mechanisms within a broader cognitive–affective–motivational system. This distinction between empirical themes and theoretical interpretation is essential for understanding not only what students experienced but also how these experiences collectively contributed to the observed improvements in creative thinking and conceptual understanding.

First, students frequently reported that visualizations and structured content reduced the difficulty of understanding complex concepts. This supports the interpretation that the intervention successfully minimized extraneous cognitive load, allowing learners to focus on essential conceptual elements. This finding is consistent with prior research indicating that effective instructional design enhances cognitive efficiency and supports deeper learning processes (Skulmowski & Xu, 2022).

Second, students described feeling more comfortable experimenting with ideas and making mistakes within the e-module environment. This suggests that the design successfully fostered psychological safety, a critical factor in supporting engagement and intellectual risk-taking in digital learning environments (Rødsgjøl et al., 2024). From an interpretative perspective, psychological safety can be understood as a mechanism that prevents cognitive resources from being diverted toward anxiety, thereby preserving cognitive capacity for creative exploration.

Third, many students reported feeling curious while interacting with the simulations, particularly when encountering unexpected outcomes. This indicates that the intervention effectively activated epistemic curiosity, which has been shown to drive engagement, inquiry, and deep learning in STEM

contexts (Stuppan et al., 2025). Curiosity, in this sense, functions as a motivational force that directs cognitive resources toward exploratory and generative processes.

Taken together, these findings suggest that conceptual understanding emerges from the interaction of cognitive, affective, and motivational mechanisms rather than from isolated factors. Based on this interpretation, a conceptual cycle can be proposed: cognitive load optimization creates cognitive headroom; psychological safety ensures that this capacity is preserved; and epistemic curiosity activates its use for exploration and idea generation. This cycle ultimately leads to enhanced creative thinking and conceptual understanding.

This integrated mechanism extends beyond traditional CLT-based explanations by incorporating affective and motivational dimensions, thereby providing a more comprehensive account of how learning occurs in complex digital environments.

IMPLICATIONS FOR QUANTUM PHYSICS EDUCATION

Building on the identified mechanisms, these findings have important implications for the design of quantum physics instruction. Quantum physics, as a domain characterized by high levels of abstraction and conceptual difficulty, requires instructional approaches that go beyond traditional content delivery to support both conceptual understanding and creative thinking.

The findings suggest that carefully designed digital learning environments can simultaneously and effectively support both conceptual understanding and creative thinking. In particular, integrating visualization, simulation, and supportive feedback mechanisms enables students to engage with abstract concepts in more intuitive and exploratory ways.

Moreover, the emphasis on psychological safety and curiosity highlights the importance of creating learning environments that encourage intellectual risk-taking and inquiry. In quantum physics, where intuitive reasoning often fails, such environments are essential for enabling students to construct new conceptual frameworks.

These findings also suggest that instructional design in quantum physics should move beyond a sole focus on content delivery toward the engineering of cognitive experiences that facilitate exploration, reflection, and conceptual restructuring. In this regard, the Design for Discovery Framework offers a practical, theoretically grounded approach to designing such environments.

CONCLUSION

Revisiting the initial pedagogical paradox between rigor and creativity in quantum physics education, this study addresses the challenge of fostering both conceptual understanding and scientific creative thinking within a cognitively demanding domain. The purpose of this research was to investigate the effectiveness of a digitally designed learning environment grounded in an integrated cognitive–affective–motivational framework.

The findings demonstrate that the implementation of the Design for Discovery e-module led to significant improvements in students' scientific creative thinking across fluency, flexibility, originality, and elaboration, as well as in their conceptual understanding of quantum physics. These results indicate that carefully structured digital learning environments can simultaneously support higher-order thinking and deep conceptual learning.

Beyond these outcomes, the study contributes theoretically by proposing the Design for Discovery Framework, which explicates how cognitive load optimization, psychological safety, and epistemic curiosity interact as a unified system to enable creative and meaningful learning. In practice, the study offers a design-oriented approach to developing instructional materials that move beyond content delivery toward the intentional engineering of cognitive and learning experiences.

Despite these contributions, the study is limited by its single-group design and relatively small sample size within a specific institutional context. Future research is therefore encouraged to employ comparative or longitudinal designs across diverse educational settings to further validate and extend the proposed framework. Additionally, exploring the integration of emerging technologies, such as adaptive systems and immersive simulations, may provide deeper insights into how to optimize learning in complex STEM domains.

In conclusion, this study highlights that effective quantum physics instruction requires more than simplifying content; it requires designing environments that enable learners to think, explore, and create within cognitively supportive and psychologically safe conditions.

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