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RESEARCH ARTICLE

Enhancing Secondary Students' Conceptual Understanding in Thermal Physics through the SCIe-GATe Inquiry Model Integrated with Immersive Technology: A Quasi-Experimental Study

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Abstract

It remains challenging to foster deep conceptual understanding in physics, particularly regarding topics such as thermal expansion. This study investigates the effectiveness of combining immersive digital technology with the SCIe-GATe enquiry model, which includes Stimulation, Conceptualization, Investigation, Generalization, and Application. Twenty-eight eleventh-grade students in Bandarlampung, Indonesia, took part in a quasi-experimental one-group pretest-posttest design. Data were collected using a validated conceptual understanding exam and classroom observations. The Wilcoxon Signed Ranks Test was employed to analyses the quantitative results, revealing a significant moderate enhancement in knowledge (N-gain = 0.46, $p < 0.001$). Qualitative data show that peak involvement happened during the enquiry and application stages, when immersive tools helped people think about model-based reasoning. This study shows that immersive enquiry frameworks can lead to new ways of teaching in situations where resources are limited. They can help students move from memorizing facts to using evidence to make decisions, even though the study has some problems because it only looked at a small number of students and didn't have a control group.

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INTRODUCTION

Developing a deep conceptual understanding in science, particularly physics, remains a significant pedagogical challenge. Students frequently struggle to comprehend abstract scientific concepts such as heat, temperature, and thermal expansion. These difficulties are often compounded by deeply rooted misconceptions that persist despite formal instruction. Research has consistently demonstrated that students tend to hold alternative mental models that are resistant to change, thereby necessitating instructional approaches that facilitate cognitive conflict and active learner engagement to reconstruct understanding effectively (Özdemir, 2022; Paçacı et al., 2023).

Özdemir (2022) proposes the utilization of animated concept cartoons as an effective pedagogical tool to induce cognitive conflict in online science learning environments. This strategy provides an engaging medium for confronting misconceptions, aligning with findings from Paçacı et al. (2023) Those who emphasize adopting innovative instructional approaches to address conceptual misunderstandings in science education.

Inquiry-based learning (IBL) has emerged as a pivotal strategy in promoting conceptual change. By involving students in the processes of scientific inquiry, IBL enables learners to engage critically with their prior knowledge and confront existing misconceptions (Aristeidou et al., 2020). Formulating research questions from everyday experiences enhances students' engagement and fosters meaningful learning outcomes. Such experiential learning approaches not only improve conceptual understanding but also contribute to long-term retention and relevance of scientific content (Kamarrudin et al., 2022).

Furthermore, social engagement is an essential component in science learning. Studies by Haw et al. (2022) and Bae & Lai (2020) have shown that student engagement in science classrooms positively correlates with motivation and academic success. Integrating collaborative and active learning strategies supports the development of a scientific community within the classroom, reinforcing both cognitive and affective dimensions of learning.

Despite the recognized benefits of these approaches, the predominant reliance on transmissive teaching methods and procedural problem-solving continues to pose significant challenges. Although such methods are commonly employed to prepare students for assessments, they often fail to cultivate deep conceptual frameworks or foster critical scientific reasoning. This limitation is particularly concerning given that passive learning environments may marginalize students who benefit from interactive, dialogic, or multimodal instructional approaches, thereby exacerbating educational inequities (Addido et al., 2022).

Recent empirical findings underscore the efficacy of innovative pedagogical strategies in enhancing conceptual understanding. Altunisik et al. (2023) demonstrate that problem- based STEM practices can significantly improve the conceptual knowledge of pre-service science teachers through active involvement in inquiry processes. Similarly, Nasir et al. (2022) report that STEM-based guided inquiry approaches facilitate students' ability to construct scientific explanations and enhance critical thinking skills. These findings advocate for the adoption of active learning strategies as a means of addressing the limitations inherent in traditional, teacher-centered instruction.

In addition, the literature highlights the inadequacies of passive learning environments and advocates for instructional reform. Nadelson et al., (2018) argue that active learning strategies enhance scientific literacy and enable learners to address and overcome misconceptions effectively. Cooperative learning settings that prioritize dialogue and collaboration are instrumental in improving both student engagement and equitable learning outcomes (Addido et al., 2022; Nadelson et al., 2018). Responsive teaching practices, incorporating students' prior knowledge and lived experiences, foster inclusivity and accommodate diverse learning styles.

Within this context, inquiry-based learning (IBL) anchored in constructivist and sociocultural theories has gained prominence as a pedagogical model that promotes meaningful engagement and conceptual development. As noted by Brugar et al. (2024) IBL positions students as active constructors of knowledge, aligning with contemporary educational paradigms emphasizing deep, inquiry-driven learning. The SCIe-GATe model, which includes phases such as Stimulation, Conceptualization, Investigation, Generalization, and Application to Make Decisions, offers a comprehensive framework for guiding students through structured scientific inquiry. This model has demonstrated effectiveness in fostering understanding, critical reasoning, and decision-making based on empirical evidence (Nugroho & Zulfiani, 2021).

Nugroho and Zulfiani (2021) further report that various IBL frameworks, such as Socio-Scientific Inquiry (SSIq) and Guided Inquiry (GI), significantly improve cognitive outcomes among high school students when compared to traditional teaching approaches. Syahgiah et al. (2023) Similarly, affirm that the application of inquiry learning promotes the development of critical thinking, enabling students to articulate scientific reasoning and internalize conceptual content more deeply.

Integrating technological tools into inquiry-based instruction further enhances students' learning experiences. Lin et al. (2022) highlights those digital technologies support collaborative inquiry by aiding students in formulating sub-questions and navigating complex problem contexts. These tools also foster increased self-efficacy through structured guidance and scaffolded learning opportunities (Hakim et al., 2023).

Moreover, advances in immersive technologies, including simulations, augmented reality (AR), and virtual laboratories, offer promising avenues for enriching inquiry-based science instruction. These tools provide students with opportunities to visualize abstract phenomena, manipulate scientific variables, and receive immediate feedback, all of which contribute to enhanced engagement and conceptual accuracy (Choon & Pang, 2021). The convergence of immersive digital media with structured inquiry models represents a significant advancement in addressing conceptual difficulties, particularly in complex topics such as thermal expansion.

Nonetheless, empirical studies that explore the systematic integration of immersive technologies into inquiry-based learning frameworks, particularly within secondary schools in developing countries, remain scarce. The present study addresses this gap by examining the effectiveness of a student worksheet developed based on the SCIe-GATe inquiry model and supported by immersive digital media, implemented in a secondary classroom in Indonesia. This research contributes to the ongoing discourse on equitable and cognitively enriching science education by proposing instructional designs that support scientific reasoning and student agency.

So, recent literature from 2020 to 2024 has consistently demonstrated the individual benefits of inquiry-based learning and the potential of immersive digital media in overcoming physics misconceptions. However, these two elements are often treated as separate entities in pedagogical practice. While prior studies have separately explored inquiry-based learning and immersive digital tools, there is currently a lack of empirical evidence regarding the systematic integration of the SCIe-GATe model within real-world physics classrooms in developing regions. This study fills this gap by examining the implementation of the SCIe-GATe inquiry model integrated with immersive technology to enhance secondary students' conceptual understanding of thermal expansion. The findings are expected to provide a replicable framework for physics educators to bridge the gap between abstract concepts and student visualization in resource-constrained environments.

METHOD

Research Design

This study employed a quasi-experimental, one-group pretest–posttest design to investigate the effects of an immersive, inquiry-based instructional intervention on students' conceptual understanding of thermal physics. Although lacking a control group, this design was chosen for its practical alignment with authentic classroom settings and compatibility with design-based science education research. This design enables within-group comparisons while maintaining ecological validity (Rainey et al., 2020).

The approach utilized allows researchers to assess the students' understanding before and after the intervention effectively, aligning with recognized methodologies in educational research (Rainey et al., 2020). This methodology has been shown to effectively gauge the impacts of specific instructional strategies on student learning outcomes (Rainey et al., 2020). Moreover, engaging students in an immersive learning environment, particularly in complex subjects like thermal physics, can profoundly enhance their conceptual grasp and reasoning capabilities (Baotong et al., 2025).

Participants and Setting

The study was conducted at a public secondary school in Bandarlampung, Indonesia. Participants included 28 eleventh-grade students (16–17) enrolled in a general physics course. The school was selected based on accessibility and willingness to collaborate in implementing pedagogical innovation. All participants were previously introduced to basic thermal concepts in the standard physics curriculum.

Instructional Intervention

The instructional sequence was designed around the SCIe-GATe inquiry model, comprising five structured phases: Stimulation, Conceptualization, Investigation, Generalization, and Application. A student worksheet was developed to guide learners through these phases, integrating immersive digital media such as interactive simulations and video-based phenomena. These elements were intended to enhance students' engagement and facilitate conceptual reconstruction through visual and interactive experiences.

- In the Stimulation phase, students were exposed to real-world phenomena through contextual videos.
- The Conceptualization phase involved guided prediction and initial explanation tasks.
- In the Investigation phase, students explored scientific models through simulations and collaborative inquiry.
- The Generalization phase focused on synthesizing findings and identifying patterns.
- The Application phase challenged students to apply concepts in decision-making tasks rooted in everyday scenarios.

This structured approach aligns with principles demonstrated in recent literature, which supports the use of inquiry-based learning as an effective method to foster deep engagement and cognitive development in students (Alarcón et al., 2023; Nzomo et al., 2023). These studies highlight the potential of immersive media to enhance the inquiry process and improve students' attitudes toward learning science (Nzomo et al., 2023). Furthermore, the integration of digital tools within inquiry-based instruction provides opportunities for students to engage in hands-on learning experiences that not only align with their interests but also stimulate critical thinking and problem-solving skills (Liu & Tsai, 2020).

Evidence from research suggests that immersive learning environments paired with effective instructional frameworks, such as the SCIe-GATe model, can lead to improved conceptual understanding among learners, particularly in complex scientific topics (Cairns, 2019). This model promotes collaboration and active participation, which are critical for developing skills necessary for scientific inquiry (Adeyele, 2023; Deák et al., 2021).

Data Collection

Multiple data sources were utilized to capture both cognitive outcomes and student experiences:

- A validated conceptual understanding test, consisting of multiple-choice items with reasoning justifications, was administered before and after the intervention.
- Classroom observations were conducted using a structured protocol to capture levels of engagement and participation.

- A student response questionnaire, comprising Likert-scale items and open-ended questions, assessed perceptions of the learning experience.
- Supplementary documentation, including video recordings and field notes, was collected to provide contextual insights into classroom dynamics.

Utilizing a combination of data sources enhances the reliability of the findings and allows for a comprehensive understanding of the instructional impact. According to Nugroho and Zulfiani, employing multiple measurement approaches in inquiry-based learning can significantly improve cognitive abilities among high school students, as it allows for a broad assessment of student engagement and (Nugroho & Zulfiani, 2021). Furthermore, integrating qualitative observations alongside quantitative assessments provides educators with deeper insights into students' experiences and learning processes (Lin et al., 2022). This multifaceted approach aligns with contemporary research emphasizing the importance of capturing diverse aspects of student learning experiences to inform instructional practices (Brugar et al., 2024).

The effectiveness of various observation methods varies, classroom observations, when documented alongside traditional assessments, can reveal how engaged students are in the inquiry process and help identify areas for instructional improvement (Nyer, 2019). The use of technology-mediated learning environments can support collaborative inquiry and facilitate real-time feedback on student understanding, which is supported by studies that highlight the positive effects of such environments on student engagement (Syahgiah et al., 2023). By employing these varied methodologies, the study aimed to provide a richer, more contextualized view of the students' learning experiences and the overall effectiveness of inquiry-based instructional strategies (Samadun et al., 2023).

Data Analysis

Quantitative data were analyzed using normalized gain (N-gain) to measure individual and group learning gains. The Wilcoxon Signed Ranks Test was employed to determine the statistical significance of pre- and posttest differences due to the non-parametric nature of the data distribution. Qualitative data from open-ended survey responses and classroom observations were thematically analyzed to identify recurring engagement patterns, cognitive conflict, and student agency. Data triangulation across sources was used to enhance the trustworthiness of findings.

The use of normalized gain (N-gain) is especially appropriate in educational research as it provides a standardized measure of gain, allowing for the assessment of learning outcomes relative to the initial learning state, a method supported by recent studies in educational assessment (Banawi et al., 2019; Sutoyo et al., 2023). Specifically, the method enables educators to determine the effectiveness of instructional interventions by providing clear insights into students' learning progress (Fitriyana et al., 2019). Furthermore, employing the Wilcoxon Signed Ranks Test is a suitable choice when dealing with non-parametric data distributions, allowing for valid comparisons between pre- and post-instructional assessments (Sesmiyanti et al., 2019)

Additionally, thematic analysis of qualitative data, including survey responses and classroom observations, allows researchers to deeply understand student experiences and engagement levels during the inquiry process (Waskita et al., 2022). This qualitative approach complements the quantitative measures by highlighting the contextual factors influencing student learning, thus reinforcing the validity of the research findings (Sutoyo et al., 2023). The data triangulation method strengthens the study's overall trustworthiness by integrating multiple perspectives and sources of data, as evidenced in recent educational research literature (Fitriyana et al., 2019; Gopalan et al., 2020).

RESULT AND DISCUSSION

Quantitative Findings: Conceptual Gains

The pre- and posttest data analysis revealed significant improvements in students' conceptual understanding of thermal expansion. The average pre-tests score was 47.5 (SD = 10.2), while the posttest mean increased to 73.9 (SD = 9.5). The average pre-tests score is 47.5 (SD = 10.2), while the average posttest increases to 73.9 (SD = 9.5), as shown in Figure 1.

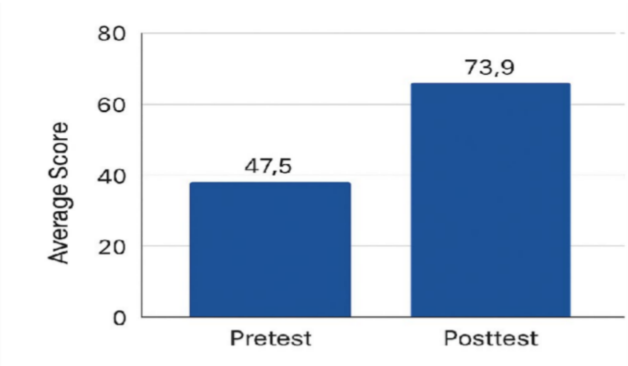

Figure 1. Pretes-Postest avarage

The calculated normalized gain score (N-gain) was 0.46, indicating a moderate level of learning gain according to Hake's criteria (Hake, 1998). This score shows that although it is not optimal, learning with the SCIe-GATe approach has successfully encouraged effective improvement in concept mastery. Figure 2 is a graph of the distribution of students' N-gain based on the category of improving conceptual understanding. Most students were in the medium category, which shows that learning with the SCIe-GATe-based worksheet is quite effective. A Wilcoxon signed-rank test was performed to test statistical significance due to non-normal data distribution. The test result yielded Z = –4.129, $p < 0.001$, confirming that the observed differences in conceptual performance were statistically significant.

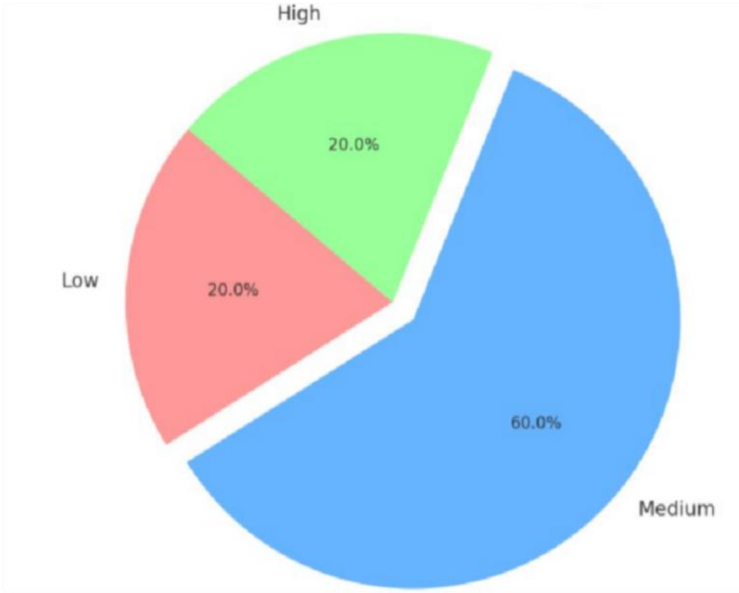

Figure 2. Distribution of n-gain

An item-level analysis further revealed substantial gains in students' ability to transfer understanding to novel situations. Pre-test responses predominantly reflected formulaic recall, while post-test answers demonstrated increased conceptual clarity, explanatory reasoning, and integration of multiple representations (e.g., visual graphs and verbal reasoning). These shifts suggest a meaningful transition from surface-level understanding to more coherent mental models of thermal processes.

The notable improvements in student responses align with findings from research indicating that effective instructional strategies, such as discovery-based learning, facilitate deeper conceptual understanding and better transfer of knowledge (Rumsariadi et al., 2023). As highlighted by Rumsariadi et al., the discovery learning model encourages student agency and enhances cognitive skills by allowing students to engage actively in their learning process, which is essential for fostering significant shifts in understanding (Rumsariadi et al., 2023). The increased complexity of students' posttest answers, characterized by enhanced explanatory reasoning and integration of various representations, supports the idea that active engagement promotes a more profound comprehension of scientific concepts.

Moreover, Hakim et al. emphasize the impact of using interactive and multimedia resources in educational settings, which can significantly enhance students' conceptual understanding and motivate them to engage with complex material (Hakim et al., 2024).

This integration of multiple forms of representation mirrors the results of this study, where students transitioned from simple recall of facts to constructing more sophisticated mental models capable of explaining thermal phenomena.

In summary, the data reflect a robust progression in student understanding that reinforces the effectiveness of inquiry-based approaches in science education. By enabling students to engage with content actively, these instructional models support the development of deeper cognitive frameworks necessary for tackling complex scientific concepts (Hakim et al., 2024)

Qualitative Findings: Student Engagement and Epistemic Practices

Qualitative data from classroom observations, student responses, and video recordings revealed high levels of engagement, particularly during the *Investigation* and *Application* phases of the SCIe-GATe model. Students worked collaboratively with simulations, formed hypotheses, and revised their ideas based on emerging evidence. Several classroom discussions illustrated moments of epistemic conflict, followed by conceptual resolution, core processes in inquiry-based learning.

Survey data supported these observations. On a 5-point Likert scale, over 85% of students agreed or strongly agreed that the immersive tools helped them visualize and understand abstract concepts. Open-ended responses further indicated that students found the experience more enjoyable, meaningful, and intellectually stimulating than traditional instruction. One student wrote, “Before, I could solve the equation, but did not get what was happening. Now I can explain it to someone else.” Such responses signal a shift in students’ epistemic stance from memorization to explanation and from passive reception to active participation in knowledge construction. This is consistent with research on student agency and sense-making in science learning environments. (Al-Gerafi et al., 2023).

From the results of the response questionnaire given to students after learning, it was obtained that 82% of students stated that they agreed or strongly agreed that the worksheet used helped them better understand the material. In addition, 89% of students found the worksheet interesting and not boring, and 75% felt motivated to discuss and experiment independently (Suyono, 2019). These findings are also reinforced by research that states that learning media that encourages students’ active involvement in inquiry activities can significantly improve literacy and conceptual understanding (Putri et al., 2021). Figure 3 is a graph of students’ responses to using a worksheet based on the SCIe-GATe model. It can be seen that aspects such as ease of use, attractiveness of worksheet, and support for conceptual understanding received a high positive response (Safitri et al., 2022).

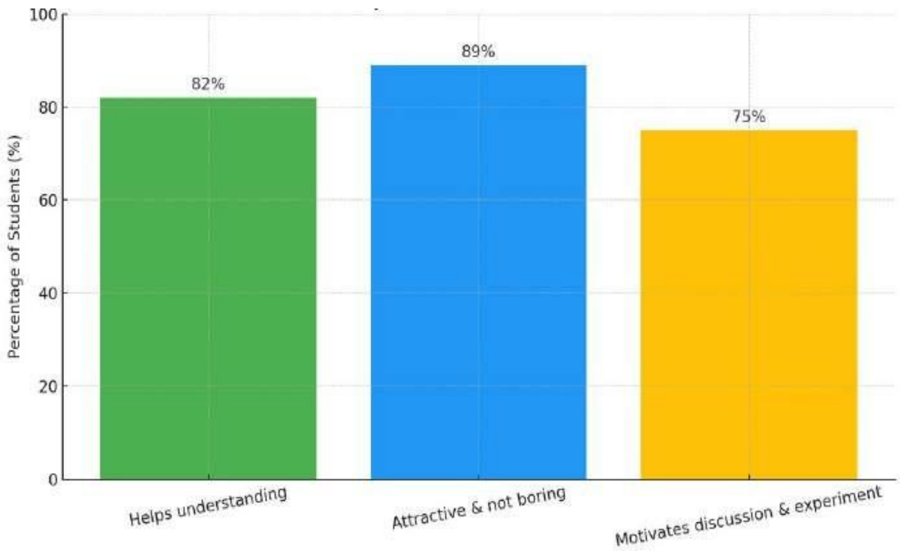

Figure 3. Student’s Response to the worksheet

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In the implementation in the classroom, several challenges were found; Some students still have difficulty formulating hypotheses and designing observation tables independently. This can be attributed to the limitations of students' experience in conducting systematic experiments (Sampson et al., 2013). Teachers need to provide scaffolding or gradual guidance so that students get used to thinking scientifically independently, as suggested by Power (2012) in his approach to discovery-based learning (Power, 2012). This challenge is an opportunity to develop the competence of the students' scientific process sustainably through the SCIe-GATe model.

The observed shift in students' attitudes towards learning has been highlighted in recent literature, which suggests that immersive tools, including augmented reality (AR) and virtual reality (VR), significantly enhance students' engagement and understanding of complex scientific concepts. These technologies allow for a more interactive and participatory learning environment that fosters deeper cognitive processing and conceptual clarity. Moreover, the alignment between the findings of this study and the research conducted by Al-Gerafi et al. underscores the crucial role that interactive and immersive tools play in enhancing students' capacities to connect abstract concepts to tangible understanding (Al-Gerafi et al., 2023).

DISCUSSION

Integrating Structured Inquiry with Immersive Media to Support Conceptual Change

The findings of this study support the growing body of research suggesting that structured inquiry models, when combined with immersive technologies, can significantly enhance students' conceptual understanding in science. The observed learning gains, as measured by N-gain and qualitative indicators, align with prior research on technology-enhanced inquiry environments (Niemelä et al., 2020). In particular, the SCIe-GATe model offers effective scaffolding by sequencing cognitive demands through inquiry phases, enabling students to move from initial observation to explanatory reasoning and decision-making.

This structured approach reflects what Windschitl et al. (2008) described as a shift from "doing science activities" to engaging in "model-based reasoning." Our results echo this claim: posttest responses and classroom observations revealed a transformation in students' epistemic orientation. Learners were no longer simply applying formulas but were engaging in reasoning about mechanisms and justifying claims with evidence. The immersive media elements also played a crucial role in facilitating this shift. Students consistently reported that visual simulations allowed them to "see" abstract processes such as particle movement or material expansion phenomena that are otherwise invisible in traditional settings. This is consistent with findings by Ainsworth (2006), who argues that multiple external representations can reduce cognitive load and foster conceptual clarity when properly integrated.

The transition to model-based reasoning indicates a significant enhancement in students' cognitive engagement, as supported by recent research on educational practices. In a study by Suh et al. (2022) The authors emphasize the importance of epistemic orientation in science education, highlighting how engaging with various representational forms can lead to deeper understanding and justification of scientific concepts (Suh et al., 2022).

This aligns with the argument that when students utilize multiple representations, they are better equipped to reason about complex mechanisms, drawing connections between abstract concepts and empirical evidence. Additionally, immersive technologies have been shown to enhance students' ability to visualize and understand challenging scientific ideas, further corroborating Ainsworth's findings regarding the cognitive benefits of multiple representations.

These shifts in pedagogical focus underscore the necessity of integrating modern, interactive teaching tools to support dynamic learning environments within science education, allowing learners to progress beyond rote memorization towards a more integrated and conceptual approach to knowledge.

Cultivating Epistemic Agency and Student ownership

Beyond cognitive gains, the study highlighted important affective and metacognitive outcomes. Students' increased willingness to generate, revise, and defend ideas indicates a rise in epistemic agency. Rather than viewing science as a fixed body of knowledge, students began participating in science as a process of inquiry, interpretation, and negotiation. This is significant in light of ongoing conversations in science education about equity and engagement; creating spaces where students can meaningfully participate in scientific discourse is central to democratizing science learning. Our data show that even in a modest classroom setting, when inquiry is carefully scaffolded and supported by rich media, students take ownership of their learning and act as scientific thinkers.

This increase in epistemic agency aligns with research suggesting that engagement in scientific practices fosters a deeper understanding and ownership of knowledge among (Odden et al., 2022; Stroupe et al., 2018). The shift from viewing science as merely a compilation of facts to a process of inquiry and negotiation reflects the ongoing discourse in educational literature about fostering equity and engagement in science education (Şengül, 2019). The findings reinforce the notion that when learners are empowered to construct and articulate their knowledge, they begin to see themselves as active participants in the scientific community (Atias et al., 2024)This resonates with the argument that classrooms designed around inquiry and collaboration can make scientific discourse more accessible and meaningful. (Davis & Bellocchi, 2018).

Moreover, enhancing scientific discourse through rich media not only supports cognitive skills but also encourages students to engage in the metacognitive processes of reflecting on their learning and (Odden et al., 2022; Stroupe et al., 2018). Implementing instructional strategies that promote epistemic agency ensures that students are not only consumers of scientific knowledge but also critical thinkers capable of contributing to the scientific dialogue that shapes our world (Erduran et al., 2021; Şengül, 2019).

Implications for Design and Pedagogical Practice

The implications of these findings are twofold. First, instructional models like SCIe-GATe can provide a replicable framework for designing inquiry-based experiences that integrate seamlessly with digital tools. This is especially valuable in contexts where teachers may lack confidence or experience designing open-ended inquiry from scratch. Second, immersive tools, while often considered resource-intensive, can be implemented effectively even in low-resource settings, provided the design is intentional and pedagogically sound.

Our results contribute to the design-based discourse in science education, demonstrating how technology can support more profound understanding and meaningful engagement as a cognitive tool rather than mere enhancement. (Tabak, 2009). Future research should explore how these tools affect long-term retention, learning transfer, and scientific identity development across diverse learners.

CONCLUSION

This study provides empirical evidence that integrating the SCIe-GATe inquiry model with immersive technology can enhance students' conceptual understanding in thermal physics. The moderate learning gains observed, alongside rich qualitative insights into student engagement and reasoning, highlight the potential of this combined approach to support meaningful science learning.

Beyond improving test scores, the intervention fostered epistemic agency by encouraging students to explain, argue, and make evidence-based decisions. These practices are central to contemporary visions of science education that emphasize knowledge acquisition and active participation in constructing scientific understanding.

The findings contribute to design-oriented research in science education by demonstrating how structured inquiry models can be paired with immersive digital media to create cognitively and socially rich learning environments. This approach offers a replicable framework for teachers aiming to move beyond traditional instruction, even in resource- constrained contexts.

Future research should examine the long-term effects of such interventions on students' conceptual retention, learning transfer, and scientific identity development. Additionally, exploring how teacher facilitation interacts with technology-supported inquiry will be critical for understanding how these models scale across diverse classrooms and cultures.

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