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PAPER

Augmented Reality and Guided Inquiry to Support 21st-Century Competencies: A Pre- and Post-Study in a Vocational Physics Module

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ABSTRACT

This study explores the potential of a physics learning module that integrates augmented reality (AR) and guided inquiry to support vocational students' development of 21st-century competencies. The module was implemented in three Indonesian vocational high schools involving 100 students, using a one-group pretest–posttest design. Students' competencies in critical thinking, creativity, communication, collaboration, and digital literacy were assessed using structured performance-based tasks before and after the intervention. Results showed statistically significant pre- and post- improvements across all assessed domains, with the most notable gains observed in collaboration ($\langle g \rangle = 0.34$, $d = 0.93$) and communication ($\langle g \rangle = 0.30$, $d = 0.78$). These within-group changes indicate promising patterns of skill development; however, the absence of a control group precludes definitive conclusions about the effectiveness of the intervention. The findings align with previous studies suggesting that immersive technologies may support 21st-century competencies, particularly when integrated within structured, inquiry-based learning environments. Caution is advised in interpreting the results as preliminary rather than conclusive. These insights may inform future instructional designs in vocational education and highlight the need for further research using more rigorous comparative designs across diverse learning contexts.

KEYWORDS

21st-century competencies, augmented reality (AR), guided inquiry, physics learning, vocational education

1 INTRODUCTION

The advent of the Industrial Revolution 4.0 has accelerated the urgency for transformative educational practices that equip students with 21st-century competencies. These competencies—critical thinking, creativity, communication, collaboration

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(collectively known as the 4C skills), and digital literacy—are essential for preparing students to navigate complex, technology-mediated environments and engage in adaptive problem solving [1], [2]. These skills are increasingly recognized as core components of educational quality and workforce readiness across diverse global contexts. However, translating these competencies into meaningful instructional practices remains a significant challenge, particularly in developing countries where systemic, infrastructural, and pedagogical limitations persist [3].

In Indonesia, vocational high schools represent a vital sector within the national education system, tasked with producing not only technically proficient graduates but also capable of critical thinking, collaboration, and creative innovation. Unfortunately, vocational instruction often remains dominated by teacher-centered pedagogies and rote memorization, with limited opportunities for students to engage in problem-based learning or collaborative inquiry actively [4], [5], [6]. This tendency restricts students' exposure to real-world problem solving and hinders the development of the soft skills demanded by the contemporary labor market. Consequently, many vocational graduates face challenges adapting to rapidly evolving work environments that require technical competence and the capacity to think independently, communicate effectively, and operate collaboratively within teams [7], [8].

Compounding this issue is the persistent reliance on conventional teaching materials and approaches that lack relevance to vocational contexts. Textbooks and worksheets often fail to connect abstract scientific principles—such as those in physics—to practical applications encountered in students' vocational training. This disconnect can diminish learner motivation and limit their ability to transfer conceptual understanding to hands-on environments. At the same time, however, vocational students are increasingly familiar with mobile technologies and digital tools, suggesting an opportunity to leverage these technologies for more engaging and contextually meaningful learning experiences.

Augmented reality (AR) is a technology that promises to transform physics instruction in vocational education. AR enables the real-time overlay of digital information—such as animations, models, or simulations—onto physical environments, creating interactive, visual, and spatial learning experiences [9], [10], [11]. These features are particularly well-aligned with the needs of vocational learners, who often benefit from concrete, visual, and task-based learning formats. AR has been shown to increase student engagement, improve motivation, and facilitate conceptual understanding when used effectively in classroom environments [9], [12]. However, the mere presence of technology does not guarantee improved learning outcomes.

The pedagogical framework within which AR is implemented is critical in mediating its effectiveness. AR can introduce extraneous cognitive load without structured instructional scaffolding, distract learners from core concepts, or lead to superficial engagement [10], [13], [14]. The Cognitive Theory of Multimedia Learning posits that multimedia tools enhance learning when they are used to promote germane cognitive processing and minimize overload [11], [15]. Similarly, research has shown that immersive technologies like virtual reality and AR may hinder learning when not accompanied by strategies such as pre-training, segmentation, or guided exploration [10], [16], [17].

To maximize the instructional benefits of AR, integration with inquiry-based pedagogies is essential. Guided inquiry learning offers a structured approach that places students at the center of the learning process while still providing essential scaffolding through teacher facilitation. In guided inquiry, students engage in scientific practices such as questioning, hypothesizing, experimenting, and reflecting, all within a framework that supports gradual autonomy [8], [18], [19]. This model fosters content knowledge and critical thinking, communication, and collaboration—key elements of 21st-century education [20], [21]. When combined with AR, guided inquiry has the potential to create immersive, exploratory environments where students actively construct understanding while interacting with dynamic visualizations of abstract phenomena.

Although a growing body of research has explored AR in science education, much of this work has focused on general secondary or tertiary education, and often emphasizes the technological development or usability of AR applications rather than their pedagogical integration [10], [22]. Empirical studies examining the impact of AR on 4C skills and digital literacy—particularly within structured inquiry frameworks in vocational school settings—remain limited. Moreover, the literature has yet to address how AR-supported inquiry learning may contribute to vocational students' specific needs and learning profiles, whose instructional contexts differ substantially from those in general education.

This study addresses these gaps by exploring how a physics learning module that integrates AR and guided inquiry may contribute to developing vocational students' 21st-century competencies. Focusing on five domains—critical thinking, creativity, communication, collaboration, and digital literacy—this study investigates patterns of change in student performance before and after engaging in AR-supported guided inquiry activities. Using a quasi-experimental one-group pretest–posttest design, the study captures within-group learning trajectories under authentic classroom conditions without drawing causal conclusions.

The study contributes to the ongoing discourse regarding the interplay between instructional media and pedagogy. While Clark [23] emphasized that learning outcomes are driven by instructional methods rather than media per se, Kozma [24] argued that media and methods are inherently linked, with specific technologies affording distinct pedagogical possibilities. This study adopts a synthetic perspective by proposing that the educational potential of emerging technologies such as AR can only be realized when embedded within structured, scaffolded learning models. In doing so, the study suggests a pedagogical framework for integrated STEM instruction that may suit the evolving needs of vocational education in the 21st century.

Given the complementary strengths of AR and guided inquiry, and the limited evidence in vocational education contexts, empirically examining how their integration affects core student competencies is important. Based on the theoretical framework and empirical needs discussed earlier, this study aims to answer the following research questions:

1. To what extent does implementing an augmented reality-based guided inquiry physics module improve vocational high school students' 4C skills (critical thinking, creativity, communication, and collaboration)?
2. To what extent does implementing the module improve students' digital literacy?
3. Which of the 4C skills shows the most significant improvement after the intervention?

2 INTEGRATING AR AND GUIDED INQUIRY: A PEDAGOGICAL RATIONALE

Rather than relying on media alone, this study adopts guided inquiry as the pedagogical scaffold that aligns with AR's affordances to support meaningful learning. AR applications may introduce extraneous cognitive load without structured guidance and hinder learning, particularly in complex domains such as physics [10], [25]. The Cognitive Theory of Multimedia Learning suggests that multimedia environments must be intentionally designed to manage intrinsic load and promote germane processing [15], [16]. Integrating AR into a guided inquiry framework ensures that technological affordances are directed toward meaningful learning activities. For example, AR simulations can be used during the exploration or concept formation stages to visualize phenomena that are otherwise invisible or difficult to demonstrate, such as electric fields or subatomic interactions [12], [26]. These visualizations become more than just attention-grabbing tools; they serve as focal points for collaborative discussion, hypothesis generation, and conceptual refinement.

Research has shown that this combination can support the development of cognitive and interpersonal competencies. Students working in groups around AR content engage in negotiation of meaning, shared problem solving, and argumentation—activities that promote critical thinking, creativity, communication, and collaboration [12], [27]. Furthermore, interacting with AR tools—such as scanning markers, navigating digital interfaces, and interpreting visual outputs—simultaneously enhances students' digital literacy [10], [26], [28].

This integration is particularly relevant in vocational education contexts. Students often learn best through hands-on, contextualized experiences, and many already possess a high familiarity with mobile devices [4]. Embedding AR within guided inquiry tasks leverages this digital familiarity and aligns learning activities with the problem-solving and collaboration required in real-world technical environments [7], [29].

The pedagogical rationale for combining AR and guided inquiry lies in their complementary strengths: AR provides immersive and visual affordances, while guided inquiry offers cognitive and collaborative scaffolding. This synergy is expected to optimize student engagement and learning outcomes, especially in domains requiring conceptual understanding and 21st-century skill development. Kyza and Georgiou [30] demonstrated that AR-supported inquiry environments not only enhance conceptual understanding but also promote learner motivation and sustained engagement—particularly when students are guided through structured exploratory tasks.

Figure 1 illustrates the conceptual integration of AR and guided inquiry within a cognitive-scaffolding framework. AR provides immersive, media-based affordances while guided inquiry structures the learning experience through four sequential phases: orientation, exploration, concept formation, and application. The pedagogical synergy is reinforced by principles from the Cognitive Theory of Multimedia Learning and Cognitive Load Theory, which emphasize minimizing extraneous processing and supporting germane learning activities. Instructional scaffolds and AR visualizations act as mediators, guiding learners toward the development of key 21st-century competencies—collectively referred to as the 4C skills—along with digital literacy.

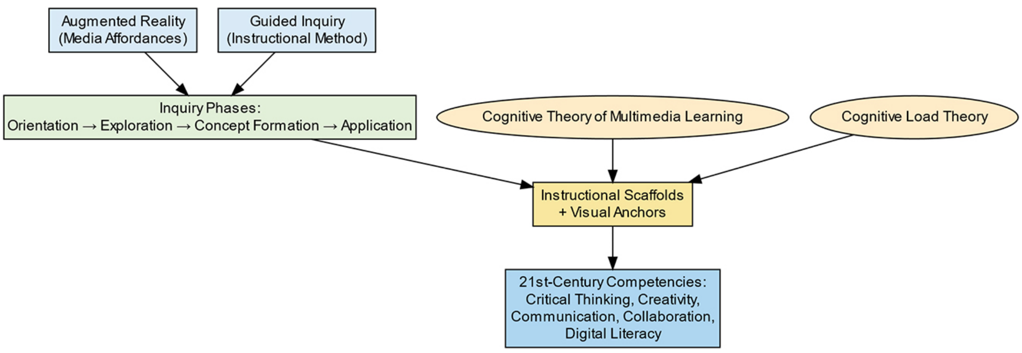

Fig. 1. Conceptual framework for integrating AR and guided inquiry

The model illustrates how AR media affordances and guided instructional phases—supported by cognitive learning theories—can facilitate the development of critical thinking, creativity, communication, collaboration, and digital literacy in vocational science education.

3 METHODS

3.1 Research design

This study employed a quasi-experimental one-group pretest–posttest design to investigate changes in students' performance across 21st-century competencies following the implementation of a guided inquiry physics module enhanced with AR. While this design is suitable for capturing within-group learning trajectories under authentic classroom conditions, it lacks the methodological rigor to establish causal relationships. No random assignment or comparison group was used; thus, any observed changes may be influenced by external factors such as teacher facilitation, group dynamics, or novelty effects. Accordingly, the analysis emphasizes descriptive patterns of improvement rather than attributing them solely to the intervention. This type of design remains useful in classroom-based research, especially when randomization is not feasible. As Bacca et al. [31] noted in their systematic review, many studies evaluating AR in education rely on quasi-experimental designs and still provide valuable evidence of learning effectiveness. Likewise, Wen et al. [12] emphasize that such designs are frequently used in evaluating AR-supported science learning under authentic conditions. We designed the intervention to foster students' 21st-century skills—specifically, critical thinking, creativity, communication, collaboration, and digital literacy—in the context of vocational physics education.

3.2 Participants

Participants were 100 students from three vocational high schools in West Sumatra, Indonesia. The schools were selected purposively based on similarity in physics curriculum, availability of student-owned mobile devices, and logistical feasibility. All participants were enrolled in the same academic year and had comparable levels of prior physics knowledge based on school records. No subgroup analyses (e.g., gender, major, or prior digital proficiency) were conducted in this study. All students had prior experience using smartphones for classroom or homework activities, which ensured baseline familiarity with digital interaction prior to AR integration.

3.3 Intervention

We developed the learning module based on the four phases of guided inquiry: orientation, exploration, concept formation, and application [8], [18]. It incorporated AR components that allowed students to visualize physics concepts through 3D animations and interactive simulations accessed via mobile devices. The AR content was delivered using marker-based mobile applications developed via the Unity engine and Vuforia. Students accessed the simulations by scanning printed markers with their smartphones, enabling immediate visualization of phenomena such as electric fields and charge interactions. The intervention was conducted over four 90-minute instructional sessions during regular classroom hours. The module focused on basic concepts in static electricity, aligned with the national physics curriculum. The implementation followed the four phases of guided inquiry—orientation, exploration, concept formation, and application—each phase structured using AR-enhanced tasks. Students worked collaboratively in small groups using AR applications installed on their smartphones. The teacher acted as a facilitator, providing structured worksheets and guiding questions, but did not offer direct instruction during the activities. During the intervention, students worked collaboratively in small groups, following inquiry-based learning procedures guided by structured worksheets. The teacher facilitated the learning process but did not directly instruct, allowing students to explore and discuss using AR features actively.

Figure 2 illustrates the sequence of the instructional intervention implemented across four class sessions. Each session aligns with a phase of guided inquiry learning—orientation, exploration, concept formation, and application—supported by AR visualizations. In Session 1, students were introduced to contextual problems and organized into collaborative groups. Session 2 involved hypothesis generation and interaction with AR simulations, while Session 3 emphasized data interpretation and group discussion. Finally, Session 4 focused on applying conceptual understanding through group presentations and reflective feedback. AR media was intentionally structured to scaffold students' engagement in scientific reasoning throughout each inquiry phase.

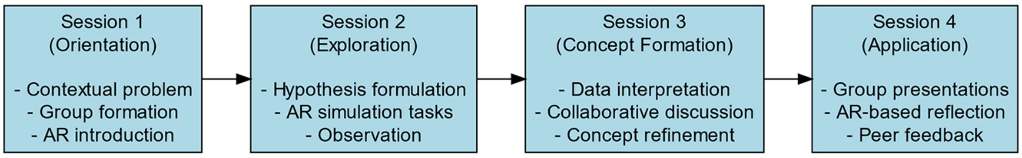

Fig. 2. Flow of the instructional intervention integrating guided inquiry and AR across four classroom sessions

Each phase includes targeted activities aligned with inquiry-based pedagogy and AR-supported tasks to promote 21st-century competencies in vocational physics education.

3.4 Instruments and measures

To evaluate students' 21st-century competencies before and after the intervention, we developed a set of structured performance-based assessments aligned with five core domains: critical thinking, creativity, communication, collaboration, and digital literacy. The assessments were embedded within the inquiry module and designed to elicit observable student performance. Each domain was evaluated using a four-point analytic rubric adapted from established P21 (Partnership for 21st Century Learning) and STEM (Science, Technology, Engineering, and Mathematics) performance frameworks, reviewed by three subject-matter experts for content validity and alignment with vocational learning goals. Engagement, motivation, or attitudinal variables were not directly measured in this study.

The performance tasks were based on the P21 framework and adapted from established performance assessment rubrics in STEM education. Each task was accompanied by a scoring rubric with analytic criteria rated on a 4-point scale (ranging from 1 = Beginning to 4 = Proficient). The rubrics were reviewed by three subject-matter experts to ensure content validity, clarity, and alignment with vocational learning objectives (see Figure 3).

Tasks for critical thinking included structured problem-solving scenarios requiring students to analyze AR simulations and justify conclusions. Creativity was assessed through open-ended tasks such as designing variations of simple experiments or offering alternative explanations for observed phenomena. Communication was evaluated through students' group presentations and clarity of argumentation during group discussions. For collaboration, evaluators assessed indicators such as role-sharing, mutual decision-making, and respectful discourse during small-group tasks. Digital literacy was assessed by observing students' ability to navigate AR tools, troubleshoot interface issues, and synthesize digital information during inquiry tasks.

These performance tasks were administered in both the pre- and post-test stages and scored by trained raters using the standardized rubric. Inter-rater reliability was established through a calibration session prior to data collection (Cohen's $\kappa > 0.80$ across all domains). By using performance-based assessments, this study aimed to capture observable evidence of competency growth rather than relying on self-perceptions.

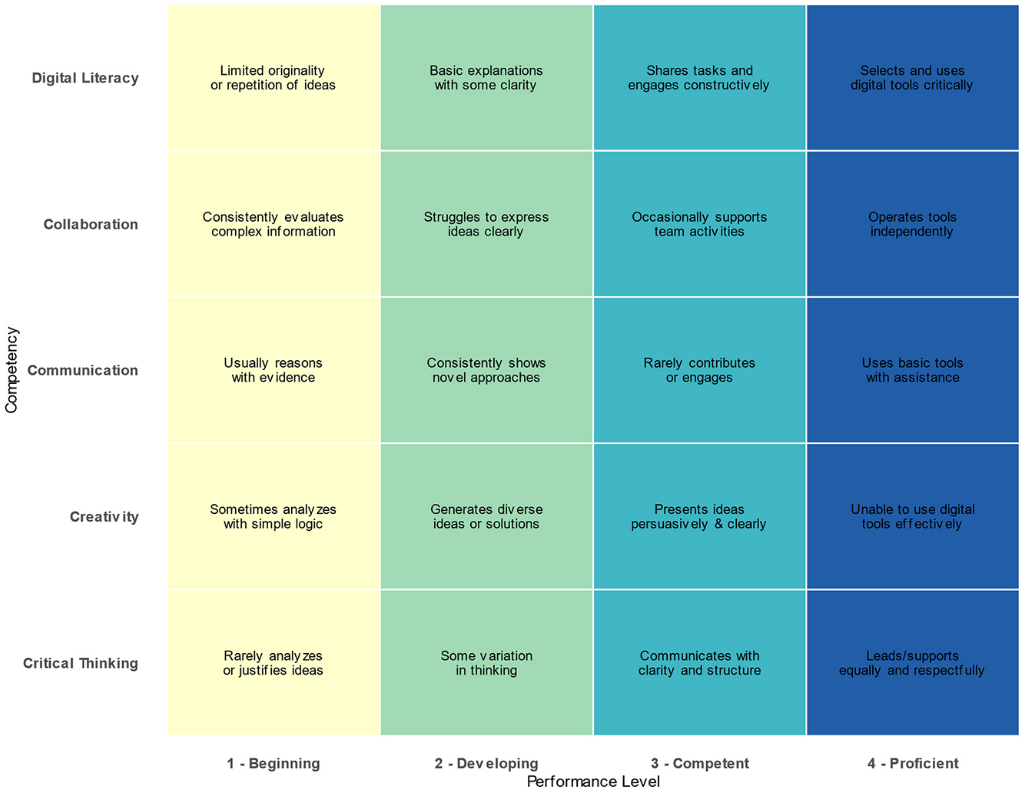

Fig. 3. Visual rubric describing performance indicators for assessing 21st-century competencies across four proficiency levels

The rubric was used to guide raters in evaluating student performance through authentic tasks aligned with critical thinking, creativity, communication, collaboration, and digital literacy.

3.5 Data collection and analysis

Data were collected at two time points: before (pre-test) and after (post-test) the implementation of the AR-based guided inquiry module. Students completed structured performance-based tasks, which were scored using standardized rubrics validated by expert reviewers. Descriptive statistics, including mean and standard deviation, were used to examine patterns of change in student competencies across the five targeted domains. To evaluate the statistical significance of observed improvements, paired-sample *t*-tests were conducted for each domain. Additionally, normalized gain scores ($\langle g \rangle$) were calculated to estimate relative improvements, using Hake's classification [32]: $\langle g \rangle < 0.3$ (low gain), $0.3 \leq \langle g \rangle < 0.7$ (moderate gain), and $\langle g \rangle \geq 0.7$ (high gain). Cohen's d was also computed to estimate the magnitude of within-group effects based on pre-to-post differences [33]. Effect sizes were interpreted according to Cohen's conventional thresholds: $d < 0.2$ (small), $0.2 \leq d < 0.5$ (moderate), $0.5 \leq d < 0.8$ (large), and $d \geq 0.8$ (very large). It is important to note that these analyses reflect within-group changes only and do not control for potential external influences such as instructor effect, group dynamics, or novelty of the AR experience. As such, the results should be interpreted as indicative rather than conclusive. All statistical computations were conducted using SPSS version 25.

4 RESULTS

This study aimed to evaluate the effectiveness of an AR-based guided inquiry module in enhancing vocational high school students' performance in five 21st-century competencies: critical thinking, creativity, communication, collaboration, and digital literacy. The data were collected through structured performance-based assessments administered before and after the intervention, and the results were analyzed to determine the extent of students' learning gains. Table 1 presents the average pre- and post-test scores, along with standard deviations and normalized gain scores ($\langle g \rangle$), for each of the five competencies. Overall, the results indicate that students made meaningful progress in all measured domains after participating in the AR-supported guided inquiry learning.

Table 1. Pre- and post-test descriptive statistics and normalized gain of 21st-century competencies (n = 100)

Competency	Pre-Test Mean (SD)	Post-Test Mean (SD)	Gain ($\langle g \rangle$)	Interpretation
Critical Thinking	66.00 (12.0)	72.00 (11.5)	0.21	Low
Creativity	65.00 (11.0)	72.00 (10.0)	0.24	Low
Communication	64.00 (12.5)	73.50 (12.0)	0.30	Moderate
Collaboration	63.00 (11.5)	73.50 (11.0)	0.34	Moderate
Digital Literacy	64.50 (11.8)	73.00 (11.2)	0.27	Low

In terms of critical thinking, the average score increased from 66.00 (SD = 12.0) to 72.00 (SD = 11.5), resulting in a normalized gain of $\langle g \rangle = 0.21$. Although this gain is categorized as low–moderate, it reflects a measurable improvement in students' ability to analyze, reason, and evaluate information during inquiry tasks. The performance-based tasks for this domain required students to interpret simulation data, justify their conclusions, and reflect on experimental results—skills that demand logical reasoning and metacognitive awareness.

Creativity scores also showed a positive trend, rising from 65.00 (SD = 11.0) to 72.00 (SD = 10.0), with a normalized gain of $\langle g \rangle = 0.24$. These tasks asked students to propose alternative designs for simple experiments and to generate novel explanations for observed physical phenomena using AR simulations. The improvement suggests that the intervention supported students' divergent thinking, even within a relatively short instructional window.

The most substantial increases were observed in communication and collaboration. Students' communication performance improved from an average score of 64.00 (SD = 12.5) to 73.50 (SD = 12.0), yielding a normalized gain of $\langle g \rangle = 0.30$. The communication tasks involved articulating ideas during group presentations, responding to peer feedback, and expressing observations clearly within a team setting. Meanwhile, collaboration scores increased from 63.00 (SD = 11.5) to 73.50 (SD = 11.0), with the highest normalized gain of $\langle g \rangle = 0.34$. Collaborative performance was assessed based on role sharing, joint decision-making, and mutual engagement in inquiry tasks. These improvements indicate that the group-based, problem-oriented learning environment fostered meaningful interpersonal interaction, likely supported by the use of shared AR visualizations.

Students also showed strong growth in digital literacy, improving from 64.50 (SD = 11.8) to 73.00 (SD = 11.2), with a normalized gain of $\langle g \rangle = 0.27$. The performance tasks in this domain evaluated students' ability to navigate AR interfaces, troubleshoot technological issues, and synthesize information from interactive simulations. This result suggests that the module helped strengthen not only technical skills but also critical engagement with digital content.

To complement the quantitative comparisons, Figure 4 provides dual visualizations of the same pre- and post-test data across the five assessed competencies. Figure 4 (left) presents a bar chart highlighting the absolute increase in average scores. In contrast, Figure 4 (right) displays a radar chart that visualizes the relative expansion of the competency profile after the intervention. Both visuals confirm the most substantial gains in communication and collaboration, reinforcing the tabular findings and offering a multidimensional view of student progress.

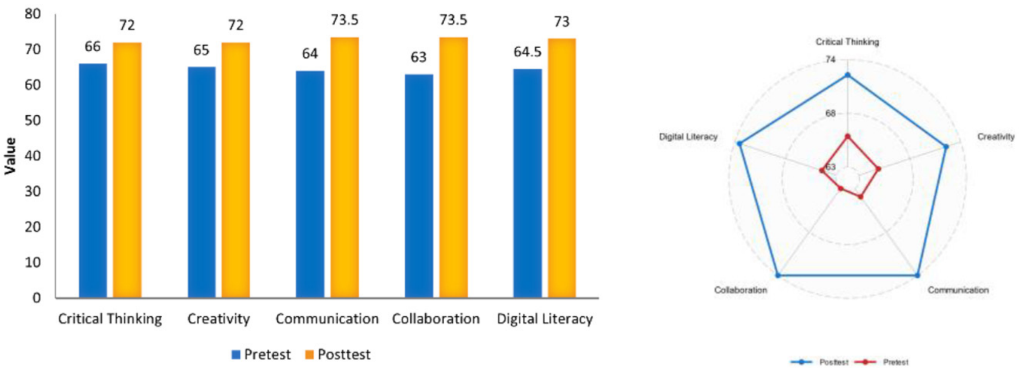

Fig. 4. Comparison of pre- and post-test scores across five 21st-century competencies

Left: bar chart showing average score improvements. Right: radar chart illustrating the expansion of students' competency profiles.

Additionally, to assess the statistical significance of these improvements, we conducted paired-sample *t*-tests for each domain, as summarized in Table 2. All five competencies showed statistically significant differences between pre- and post-test scores ($p < .001$). The effect sizes, calculated using Cohen's *d*, ranged from 0.53 (critical thinking) to 0.93 (collaboration), with communication and digital literacy also showing large effects ($d > 0.70$). While these results indicate substantial within-group improvements, they should not be interpreted as definitive evidence of intervention effectiveness due to the absence of a comparison group. It remains possible that observed gains were influenced by factors unrelated to the instructional module, such as motivational novelty, peer dynamics, or instructor facilitation.

Taken together, the results provide preliminary indications that the integration of AR and guided inquiry may offer a meaningful context for students to practice and demonstrate key 21st-century competencies through authentic tasks, although the absence of a control group limits the strength of causal inferences. The observed gains across all domains indicate that even in the absence of a control group, the structured performance-based approach offers a valid means to capture students' actual skill development in response to innovative instructional designs.

Table 2. Paired-sample t-test results and effect sizes for 21st-century competencies (n = 100)

Competency	*t*-Value	df	*p*-Value	Cohen's *d*	Effect Size Interpretation
Critical Thinking	5.22	99	<.001	0.53	Large
Creativity	6.36	99	<.001	0.67	Large
Communication	6.80	99	<.001	0.78	Large
Collaboration	7.10	99	<.001	0.93	Very Large
Digital Literacy	6.50	99	<.001	0.74	Large

We also conducted paired-sample *t*-tests comparing pretest and posttest scores for each competency to determine whether the improvements were statistically significant (refer to Table 2). All five competencies showed statistically significant improvements ($p < .001$), confirming that the observed learning gains were not due to chance. Moreover, the effect sizes (Cohen's d) were large across the board, with values ranging from 0.53 to 0.93. According to Cohen's guidelines, values above 0.8 represent large effects, indicating strong practical significance. The large effect size in collaboration ($d = 0.93$) reflects a notable shift in observed group performance; however, such magnitudes are relatively uncommon in short-term educational interventions and may reflect novelty effects or contextual influences rather than the instructional module itself.

Although the study employed structured, rubric-based assessments with established inter-rater reliability, all scoring was conducted by observers who were familiar with the intervention's purpose and implementation. This familiarity may have introduced observer bias or expectancy effects, particularly in the absence of blind scoring procedures—a common threat to internal validity in classroom-based studies [34], [35]. Moreover, external influences such as teacher facilitation style, peer dynamics, and the novelty of AR technology may have also affected student performance independently of the instructional design. These factors underscore the importance of experimental controls and methodological triangulation. To enhance the robustness of future research, it is recommended to employ blind assessment protocols, randomized group assignments, and multiple data sources including observational logs or longitudinal follow-up measures to assess sustained learning outcomes.

Furthermore, although normalized gain scores in this study suggest only low to moderate relative improvements ($\langle g \rangle < 0.35$), the corresponding effect sizes based on Cohen's *d* are generally large. This apparent discrepancy reflects the different assumptions and sensitivities of each metric. Normalized gain evaluates improvement relative to the distance between pretest scores and the maximum possible score, making it sensitive to ceiling effects and initial proficiency levels. In contrast, Cohen's *d* measures standardized mean differences and can appear large when score variability is low and gains are consistent, even if absolute improvements are modest. Therefore, while both metrics are valid, they serve different interpretive functions. Normalized gain provides insight into learning efficiency relative to the scale, whereas Cohen's *d* emphasizes the magnitude of change in standardized terms. Taken together, they suggest that although most students improved, the room for growth in certain domains may have been limited by task ceiling or short intervention duration.

5 DISCUSSION

This study examined the potential contribution of an AR-based guided inquiry module to the development of vocational students' 21st-century competencies. The results showed statistically significant pre-to-post improvements across all measured domains—critical thinking, creativity, communication, collaboration, and digital literacy—as assessed through structured performance-based tasks. While causal claims cannot be made due to the one-group design, these findings suggest that combining immersive media with inquiry-driven pedagogy may support meaningful skill development in vocational science education.

The most substantial gains were observed in communication and collaboration. These competencies improved significantly after students engaged in small-group inquiry tasks supported by AR simulations, indicating that socially embedded learning environments can foster interpersonal skill development. Throughout the intervention, students were encouraged to discuss observations, negotiate meaning, and present group findings—activities that required verbal articulation and joint decision-making. The improvement in these domains aligns with the socio-constructivist view of learning, which emphasizes that knowledge construction is mediated through social interaction and shared tools [36]. Kyza and Georgiou [30] also reported that AR-supported inquiry platforms enhance student engagement and conceptual understanding, particularly when structured around collaborative meaning-making. AR visualizations provided a standard reference that anchored group discussions and helped reduce ambiguity, supporting more transparent communication and cohesive teamwork.

In addition to interpersonal competencies, students demonstrated measurable gains in digital literacy. The performance tasks required them to scan AR markers, navigate mobile applications, troubleshoot digital obstacles, and interpret dynamic visualizations in real time. These activities engaged students in both operational and evaluative dimensions of digital literacy [28], [37], [38]. Previous studies have noted that AR-supported inquiry tasks—especially those in authentic and exploratory contexts—can help bridge the gap between students' everyday technology use and academic digital competence [9], [25]. The results of this study reinforce that AR can serve not only as a content delivery medium but also as a tool to cultivate critical digital skills required in the modern workplace [1], [29].

Although the effect sizes for critical thinking and creativity were moderate, the corresponding normalized gain scores were relatively low ($\langle g \rangle = 0.21$ and 0.24, respectively), indicating that students made only limited relative progress in these higher-order competencies. This limitation may stem from the inherently complex and abstract nature of these skills, which typically require extended periods of iterative practice, metacognitive reflection, and open-ended exploration to develop meaningfully. The four-session intervention, while structured and engaging, may have prioritized procedural collaboration and digital interaction over sustained analytical or generative thinking. Future iterations of the module should consider incorporating longer implementation periods, more divergent problem-solving tasks, and explicit scaffolding for critical reflection to better foster these cognitive outcomes. Nonetheless, the inquiry tasks—which required hypothesis generation, data interpretation, and explanatory reasoning—may have laid foundational experiences for higher-order thinking skills [39], [40], [41]. Guided inquiry phases, such as exploration and concept formation, have scaffolded students' reasoning processes by structuring opportunities for analytical and generative thought [18], [19]. These findings are consistent with prior work showing that inquiry models can initiate higher-order thinking development when properly supported [42], [43].

From a theoretical standpoint, the design of the module aligns conceptually with the Cognitive Theory of Multimedia Learning and principles from Cognitive Load Theory, which emphasize the importance of minimizing extraneous cognitive load and supporting meaningful visual processing [15], [44]. While the study did not directly assess cognitive load, the use of segmented tasks, peer scaffolding, and guided inquiry phases was intended to manage the complexity introduced by AR media [10], [13], [23]. These instructional elements may have contributed to learners' engagement and task focus, but further empirical work is needed to examine these mechanisms explicitly. This pedagogical structure aligns with research by Meyer et al. [16], who emphasized the role of pre-training and task sequencing in reducing cognitive overload in immersive learning environments. The students were not passive consumers of AR but active explorers within a supportive framework, a combination shown to optimize learning outcomes [12], [27].

These results are particularly relevant for vocational education settings, where integrating soft skills into technical instruction remains challenging [5], [6]. Traditional vocational classrooms often rely on teacher-centered methods with limited opportunities for collaboration or inquiry [4], [7]. The observed gains suggest that technology-enhanced inquiry learning holds potential as an instructional approach for supporting vocational students' development of workplace-relevant competencies. While the improvements in collaboration and digital literacy are encouraging, the findings should be interpreted as indicative rather than conclusive due to the study's limited scope and design. These preliminary outcomes may inform future efforts to align vocational science instruction with broader Education 4.0 goals [1], provided they are supported by more rigorous, longitudinal evidence [45].

Nonetheless, this study has certain limitations. While appropriate for initial classroom-level interventions, a one-group pretest-posttest design limits causal inference. Although the large effect sizes observed suggest substantial impacts, the absence of a control group prevents definitive attribution. Additionally, the study did not examine subgroup variations (e.g., gender or prior digital experience), which could be explored in future research. The performance assessments, though rubric-based and expert-validated, also require further triangulation with observational or longitudinal data to confirm sustained competency development over time.

The results provide preliminary evidence that integrating AR with guided inquiry pedagogy may support the development of observable 21st-century competencies among vocational students. By aligning immersive technology with structured scientific tasks, the learning experience may become both cognitively engaging and socially meaningful. Although not designed to test theoretical claims directly, the study's findings resonate with the argument that instructional methods and technological tools must be coherently aligned to promote meaningful learning [23], [24]. The integration of AR within guided inquiry tasks appeared to support student engagement and performance; however, these observations remain context-specific and should not be generalized without further comparative investigation.

5.1 Applications and recommendations

The results of this study suggest several actionable implications for vocational science education stakeholders. First, for teachers and instructional designers, integrating AR within guided inquiry frameworks may offer a feasible pathway to develop students' collaboration, communication, and digital literacy skills. The improvement observed in these domains was powerful, indicating that structured, media-supported group tasks can foster essential 21st-century competencies. However, the relatively modest gains in critical thinking and creativity point to the need for extended instructional time and more open-ended inquiry tasks in future implementations. Second, curriculum developers should consider embedding performance-based assessments aligned with 4C competencies and digital literacy. Rubric-guided, observable tasks—rather than traditional multiple-choice or perception-based instruments—enable more accurate evaluation of students' applied skills. The use of AR tools should be planned around the inquiry phases to ensure that technological engagement aligns with learning objectives and does not generate extraneous cognitive load. Third, education authorities and school leaders may explore low-cost AR implementations using widely available mobile devices, supported by professional development that equips teachers to facilitate guided inquiry. As the study showed, the impact of AR depends not only on access to technology but also on how it is pedagogically structured. Investments in capacity-building for inquiry facilitation may yield better outcomes than hardware alone. Finally, developers of AR educational content are advised to co-design materials in collaboration with educators to ensure alignment with inquiry-based models. Features like visual prompts, scaffolded exploration, and integrated reflection tools can enhance usability while supporting deeper learning. Moving forward, further studies should investigate the scalability of such interventions, explore differentiated effects across student profiles, and incorporate longitudinal designs to assess sustained competency development. Future work may also address implementation challenges in settings with limited infrastructure or diverse learner needs.

6 CONCLUSION

This study explored vocational high school students' development of 21st-century competencies after participating in an AR-based guided inquiry physics module. Significant pre-to-post improvements were observed in collaboration, communication, and digital literacy, with more modest gains in critical thinking and creativity. These findings, derived from structured rubric-guided performance assessments, offer preliminary evidence that immersive, inquiry-oriented instruction may be associated with the development of selected 21st-century competencies in vocational learning contexts. While the AR simulations appeared to function as shared visual anchors that supported collaborative engagement, and the guided inquiry structure provided a scaffolded learning environment, these interpretations remain speculative. Without a control group or longitudinal tracking, it is not possible to determine the specific contribution of the instructional module to the observed improvements. As such, the results should be interpreted as indicative patterns under specific classroom conditions rather than as conclusive evidence of intervention effectiveness. However, as the study did not include a control group or long-term tracking, these patterns should be interpreted cautiously. While the study aligns conceptually with multimedia learning and cognitive load theories, it did not directly measure students' processing load or long-term cognitive gains. Therefore, any theoretical implications remain inferential. In practical terms, the intervention design offers an potentially valuable model for further research, though additional studies are needed to validate its impact across diverse settings, durations, and learner profiles. Future work should include control or comparison groups, examine differential effects based on learner characteristics, and assess the sustainability of observed skill development. Within these limitations, the current study contributes early evidence toward integrating immersive technologies and structured inquiry as complementary elements in vocational science education.

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