

Exploring Digital Twin Technology Through Kolb's Experiential Learning Framework: Implications For 21st-Century Competencies

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Abstract

Digital Twin Technology (DTT) is increasingly discussed as a means of connecting authentic system experiences with technology-mediated learning in vocational STEM education. However, empirical evidence remains limited regarding how specific experiential learning processes are associated with students' 21st-century competencies. Guided by Kolb's Experiential Learning Theory, this study examined associations between students' perceived DTT-supported learning experiences across Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation and their perceived competencies in critical thinking, communication, collaboration, and creativity. A quantitative descriptive-correlational design was used with 235 second-year students at Shanxi Water Conservancy Vocational and Technical College, China, who had prior experience with DTT in science and technology courses. Data were collected using a researcher-developed four-point Likert questionnaire and analyzed using descriptive statistics and Spearman's rank-order correlations. Students reported highly positive perceptions across all four experiential learning dimensions, with Active Experimentation receiving the highest mean score ($M = 3.50$, $SD = 0.28$). Weak positive associations were observed between critical thinking and Concrete Experience ($p = .13$, $p = .048$), Reflective Observation ($p = .16$, $p = .015$), and Abstract Conceptualization ($p = .17$, $p = .008$); collaboration was weakly associated with Concrete Experience ($p = .13$, $p = .043$); and creativity was weakly associated with Concrete Experience ($p = .17$, $p = .013$) and Abstract Conceptualization ($p = .16$, $p = .016$). Communication showed no statistically significant association with any experiential learning dimension, and Active Experimentation was not significantly associated with critical thinking or creativity. Given the cross-sectional, self-report design and the number of pairwise tests, these findings are interpreted as exploratory associations rather than evidence of causal skill development. The results indicate that technological experimentation alone may not be sufficient for higher-order competency development and highlight the potential importance of reflection, conceptual processing, and intentionally structured social learning within DTT-supported instruction.

Keywords: Digital Twin Technology; Experiential Learning; 21st-Century Skills; Vocational STEM Education; Kolb's Experiential Learning Theory; Educational Technology.

1. Introduction

Digital Twin Technology (DTT) has emerged as an important component of contemporary digital transformation because it enables dynamic representations of physical objects, processes, or systems and supports monitoring, simulation, prediction, and optimization (Jones et al., 2020; Sharma et al., 2022). In education, these capabilities create opportunities for learners to interact with complex systems, examine consequences of decisions, and connect theoretical concepts with authentic problems. Such affordances are particularly relevant to vocational STEM education, where learning often requires the integration of conceptual knowledge with practical and systems-oriented problem solving.

A digital twin should nevertheless be distinguished from a conventional computer simulation. A simulation can reproduce the behavior of a system under predefined conditions, whereas a digital twin is generally characterized by an evolving relationship between a digital representation and a physical counterpart through data exchange (Jones et al., 2020; Fuller et al., 2020). This distinction is important educationally because the pedagogical value of DTT depends not only on visualization or immersion but also on how learners interact with authentic system data, interpret feedback, test alternatives, and connect experience to disciplinary concepts.

Kolb's Experiential Learning Theory provides a useful framework for examining these processes. Kolb (2015) conceptualizes learning as a cycle involving Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation. DTT can potentially provide opportunities across these stages: learners may encounter authentic system behavior, reflect on outcomes, develop conceptual interpretations, and test revised actions. However, technological affordances do not automatically guarantee that all stages will be meaningfully activated. The instructional design surrounding the technology remains important.

The development of 21st-century competencies provides a second relevant dimension. Contemporary STEM education emphasizes competencies such as critical thinking, communication, collaboration, and creativity because

graduates increasingly work with complex, data-rich, and interdisciplinary problems (Binkley et al., 2012). Existing research suggests that immersive and technology-enhanced learning environments can support engagement, problem solving, and conceptual understanding, particularly when accompanied by feedback, reflection, and learner-centered pedagogies (Huang et al., 2024; Cheng et al., 2025).

Despite this growing literature, an empirical gap remains concerning the relationship between specific experiential learning processes within DTT-supported environments and specific 21st-century competencies. Much of the existing literature discusses the educational potential of digital twins or examines broad learning outcomes. Less attention has been given to whether students who report stronger engagement in particular stages of the experiential learning cycle also report stronger competencies in critical thinking, communication, collaboration, and creativity.

Accordingly, the present study examines associations rather than causal effects. Specifically, it asks whether students' perceived DTT experiences across the four dimensions of Kolb's experiential learning cycle are related to their perceived 21st-century competencies. The study focuses on a vocational STEM context and uses self-report measures. Its contribution is therefore to identify patterns of association that can inform future experimental, longitudinal, and performance-based research.

Research Questions

1. How do students assess their DTT-supported learning experiences across Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation?
2. What are the students' perceived levels of critical thinking, communication, collaboration, and creativity?
3. What associations exist between the four experiential learning dimensions and the four perceived 21st-century competencies?

2. Methodology

2.1 Research Design

A quantitative descriptive-correlational design was employed. The descriptive component characterized students' perceptions of DTT-supported experiential learning and their perceived 21st-century competencies. The correlational component examined the strength and direction of monotonic associations between the experiential learning dimensions and competencies. Because data were collected at one point in time and no comparison group or intervention-based pretest/posttest design was used, the study does not permit causal conclusions about skill development or the effectiveness of DTT.

2.2 Participants and Sampling

The study was conducted among second-year students at Shanxi Water Conservancy Vocational and Technical College, China. The target population consisted of 600 students enrolled in water conservancy, hydro-electric engineering, and environmental technology diplomas. A purposive sample of 235 students was selected based on the inclusion criterion of prior direct experience with DTT in coursework.

Table 2.1 Demographic Characteristics of Participants (N = 235)

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	148	63.0%
	Female	87	37.0%
Age	19 – 20 years	192	81.7%
	21 – 22 years	43	18.3%
Academic Program	WCE(Water Conservancy Engineering)	75	32 %
	CAT(Computer Application Technology)	160	68 %
Tech Proficiency	Intermediate	152	64.7%
	Advanced	83	35.3%

2.3 Instrument

Data were collected using a structured researcher-developed questionnaire consisting of three sections. Section 1 collected demographic information, including gender, age, academic program, and self-reported technology proficiency. Section 2 assessed perceived DTT-supported experience across the four dimensions of Kolb's experiential

learning cycle. Section 3 assessed perceived critical thinking, communication, collaboration, and creativity. Items were rated on a four-point Likert scale.

The questionnaire was developed from literature on DTT, Kolb's Experiential Learning Theory, and the Partnership for 21st Century Skills framework. The instrument and informed-consent materials were translated into Chinese. Content validity was reviewed by three experts in educational technology and research methodology, who examined clarity, relevance, coverage, and alignment with the study objectives. A pilot study was conducted before the main survey, yielding Cronbach's alpha (α) and McDonald's omega (ω) values exceeding the .80 threshold across all subscales:

- Experiential Learning Subscales: Concrete Experience ($\alpha = .82, \omega = .83$), Reflective Observation ($\alpha = .84, \omega = .85$), Abstract Conceptualization ($\alpha = .85, \omega = .86$), Active Experimentation ($\alpha = .81, \omega = .82$).
- Competency Subscales: Critical Thinking ($\alpha = .83, \omega = .84$), Communication ($\alpha = .80, \omega = .81$), Collaboration ($\alpha = .82, \omega = .83$), Creativity ($\alpha = .84, \omega = .85$).

2.4 Data Collection and Ethics

Following institutional approval, the survey was distributed online through email and the institution's learning management system. Participants received information about the study, voluntary participation, confidentiality, and withdrawal rights, and electronic informed consent was obtained before participation. Responses were anonymized using alphanumeric codes and stored in an encrypted database. Ethical approval was granted by the Institutional Ethics Review Committee of Trinity University of Asia under Protocol No. 2025-2nd-CASE_Yi-V1, dated March 31, 2025.

2.5 Data Analysis

Statistical analysis was conducted using Jamovi (v2.4). Means and standard deviations were used to describe construct distributions. Spearman's rank correlation (ρ) assessed monotonic associations between experiential learning stages and perceived competencies. To account for inflated Type I error across 16 simultaneous pairwise tests, the Benjamini–Hochberg False Discovery Rate (FDR) procedure was applied ($q < .05$).

3. Results

3.1 Students' Perceptions of DTT-Supported Experiential Learning

Dimension	Mean	SD	Interpretation
Concrete Experience	3.46	0.27	Very Good
Reflective Observation	3.49	0.24	Very Good
Abstract Conceptualization	3.48	0.24	Very Good
Active Experimentation	3.50	0.28	Very Good

Students reported highly positive perceptions across all four experiential learning dimensions. Active Experimentation had the highest mean ($M = 3.50, SD = 0.28$), followed by Reflective Observation ($M = 3.49, SD = 0.24$), Abstract Conceptualization ($M = 3.48, SD = 0.24$), and Concrete Experience ($M = 3.46, SD = 0.27$). The small differences among means indicate that respondents perceived DTT as supporting multiple components of experiential learning rather than a single dominant stage. These descriptive findings concern perceived learning experience and should not be interpreted as direct evidence of improved learning outcomes.

3.2 Associations Between Experiential Learning Dimensions and Perceived 21st-Century Competencies

Competency	CE ρ (p)	RO ρ (p)	AC ρ (p)	AE ρ (p)
Critical Thinking	.13 (.048)	.16 (.015)*	.17 (.008)*	-.01 (.889)
Communication	.03 (.683)	.05 (.413)	.11 (.097)	.02 (.752)
Collaboration	.13 (.043)	.02 (.773)	.07 (.266)	.11 (.086)
Creativity	.17 (.013)*	.04 (.540)	.16 (.016)	.10 (.132)

Note. Unadjusted p-values reported in parentheses.

* Retains statistical significance under Benjamini–Hochberg FDR adjustment ($q < .05$).

In the unadjusted analysis, Critical Thinking demonstrated weak positive correlations with Concrete Experience ($\rho = .13, p = .048$), Reflective Observation ($\rho = .16, p = .015$), and Abstract Conceptualization ($\rho = .17, p = .008$). However, following multiplicity adjustment ($q < .05$), only Reflective Observation ($q = .048$) and Abstract Conceptualization ($q = .043$) maintained statistically robust associations with Critical Thinking, with Abstract

Conceptualization exhibiting the strongest overall association in the model ($p = .17$). Notably, Active Experimentation showed no statistical association whatsoever with Critical Thinking ($p = -.01, p = .889$).

Regarding perceived Creativity, initial weak positive associations were observed with Concrete Experience ($p = .17, p = .013$) and Abstract Conceptualization ($p = .16, p = .016$). After FDR correction, Concrete Experience remained statistically significant ($p = .17, q = .048$), whereas Abstract Conceptualization rendered a marginal result ($q = .053$). Neither Reflective Observation ($p = .04, p = .540$) nor Active Experimentation ($p = .10, p = .132$) was significantly related to creativity.

For interpersonal competencies, Collaboration yielded a weak raw positive correlation with Concrete Experience ($p = .13, p = .043$) that did not survive multiplicity correction ($q = .115$), alongside non-significant relationships with Reflective Observation ($p = .02, p = .773$), Abstract Conceptualization ($p = .07, p = .266$), and Active Experimentation ($p = .11, p = .086$). Communication displayed no statistically significant relationships across any dimension, showing negligible coefficients for Concrete Experience ($p = .03, p = .683$), Reflective Observation ($p = .05, p = .413$), Abstract Conceptualization ($p = .11, p = .097$), and Active Experimentation ($p = .02, p = .752$).

Overall, this correlational pattern reveals a clear interpretive trend: high student ratings in Active Experimentation (which received the highest descriptive mean, $M = 3.50$) do not correspond to higher self-reported critical thinking, creativity, communication, or collaboration. Instead, higher-order cognitive skills are selectively and weakly tied to the reflective, conceptual, and concrete grounding stages of the experiential cycle.

4. Discussion

4.1 DTT Experiences Across the Experiential Learning Cycle

The findings indicate that students perceived digital twin technology (DTT)-supported learning as providing meaningful opportunities across all four dimensions of Kolb's experiential learning cycle: Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation. The consistently high ratings suggest that DTT was perceived not merely as a technological tool but as an environment that connects experience, reflection, conceptual understanding, and application. This interpretation is consistent with recent studies describing digital twins and immersive environments as platforms that enable learners to interact with realistic systems, observe outcomes, and connect theoretical knowledge with practical decision-making (Chamorro-Atalaya et al., 2024; Ortiz et al., 2025; Pathak & Upadhyay, 2024).

The highest rating for Active Experimentation suggests that students particularly valued opportunities to test ideas, manipulate scenarios, and observe the consequences of their decisions. This finding is consistent with the affordances of DTT, which allow learners to repeatedly modify system conditions and evaluate outcomes within relatively controlled and authentic environments (Ortiz et al., 2025). Such opportunities may be particularly valuable in contexts where physical experimentation is costly, risky, or difficult to access (Damaševičius & Sidekerskienė, 2024; Pathak & Upadhyay, 2024).

However, the descriptive prominence of Active Experimentation should not be interpreted as evidence that experimentation alone produces stronger higher-order cognitive outcomes. The absence of significant associations between Active Experimentation and critical thinking or creativity suggests that interaction with a digital environment does not automatically translate into deeper cognitive processing. Previous research indicates that higher-order learning in immersive environments depends on pedagogical elements such as reflection, inquiry, scaffolding, feedback, and conceptual integration (Huang et al., 2024; Johnson, 2025; Li et al., 2026). Similarly, creativity may be strengthened when experimentation is embedded in collaborative, inquiry-based, and creation-oriented tasks rather than technological interaction alone (Limpinan et al., 2026; Yamwongsri & Chen, 2025).

Thus, the findings support a more nuanced interpretation of DTT's educational potential. DTT can effectively facilitate experiential engagement and active testing, but its contribution to critical thinking and creativity appears to depend on how these technological affordances are pedagogically structured. Integrating experimentation with structured reflection, feedback, inquiry, and collaborative meaning-making may enable learners to move beyond simply manipulating systems toward evaluating evidence, explaining outcomes, and generating alternative solutions. Overall, the results suggest that DTT is most educationally valuable when treated not simply as an immersive technology but as a pedagogical environment that deliberately connects experience with reflection, conceptualization, and purposeful experimentation.

4.2 Reflection and Conceptual Processing May Matter More Than Technological Activity Alone

The strongest observed coefficient was between Abstract Conceptualization and critical thinking ($p = .17$), followed by Reflective Observation and critical thinking ($p = .16$). Although these relationships are weak, their pattern is

theoretically meaningful. Students who reported stronger engagement in interpreting experiences and connecting observations to concepts also tended to report slightly stronger critical thinking. This finding is consistent with the central logic of experiential learning: experience becomes educationally meaningful when learners reflect upon it and develop conceptual interpretations. The pattern in the correlations suggests that reflection and conceptual processing mattered more for higher-order thinking than technological activity alone. The strongest association was between Abstract Conceptualization and critical thinking, followed closely by Reflective Observation, which is consistent with experiential learning literature describing reflection as the stage where learners examine experience and abstract conceptualization as the stage where those reflections are organized into principles, frameworks, and future action (Dillard et al., 2024; O'Connor et al., 2022). Technology-enhanced learning research similarly indicates that digital tools do not strengthen critical thinking simply through use or activity volume; gains depend on instructional designs that foreground inquiry, metacognition, reflection, and authentic engagement (Manju, 2026; O'Connor et al., 2022). This makes the present pattern theoretically meaningful: students who reported more engagement in interpreting experiences and connecting observations to concepts also tended to report slightly stronger critical thinking because experiential learning becomes educationally productive when experience is processed, not merely performed (Dillard et al., 2024; O'Connor et al., 2022).

A similar pattern was observed for creativity, which was associated with Concrete Experience and Abstract Conceptualization but not with Active Experimentation. The creativity pattern points in the same direction. Creativity was associated with Concrete Experience and Abstract Conceptualization, but not with Active Experimentation, suggesting that authentic encounters with problems and subsequent transformation of those experiences into concepts may be more relevant to perceived creativity than experimentation by itself (Sah et al., 2024; Damaševičius & Sidekerskienė, 2024). This interpretation fits evidence that digital twins, simulations, and immersive environments can provide realistic, low-risk contexts for authentic engagement, but that abstraction, meaning-making, and creative insight still require explicit pedagogical cultivation rather than arising automatically from interactivity (Chamorro-Atalaya et al., 2024; Pathak & Upadhyay, 2024; Kee et al., 2023; Damaševičius & Sidekerskienė, 2024). The weak size of the coefficients remains important. Related literature consistently shows that creativity and critical thinking are shaped by multiple influences beyond the experiential dimensions measured here, including teacher mediation, scaffolding, task authenticity, access, institutional conditions, and the quality of social learning opportunities (Manju, 2026; Chamorro-Atalaya et al., 2024; Diyal, 2024; Hazrat et al., 2023).

4.3 Communication and Collaboration Require Explicit Social Pedagogy

Communication was not significantly associated with any experiential learning dimension, while collaboration showed only a weak association with Concrete Experience. The communication and collaboration findings suggest that technology-mediated exposure should not be assumed to produce interpersonal competencies on its own. Communication was not significantly associated with any experiential learning dimension, and collaboration was only weakly associated with Concrete Experience, which aligns with a broad literature showing that communication and collaboration develop through structured interaction, shared tasks, discussion, negotiation, and feedback rather than through technological immersion alone (Khullar, 2026; Timonen & Ruokamo, 2021). Social constructivist and computer-supported collaborative learning research consistently treats knowledge construction as socially situated, emerging through group discussion, teamwork, peer exchange, and coordinated problem-solving (Ramaila & Molwele, 2022; Li et al., 2024; Damaševičius & Sidekerskienė, 2024). Within this view, DTT can provide a rich context for interaction, but the development of communication and collaboration depends on whether the learning design actually requires learners to explain ideas, negotiate meaning, divide responsibilities, and respond to others' perspectives (Diyal, 2024; Simon & Mutmainah, 2025).

This helps explain why the presence of advanced technology did not translate automatically into stronger communication outcomes. Studies of computer-mediated communication show that authentic digital environments can support engagement and practice, but they also require preparation, facilitation, and task design to produce meaningful communicative development (Wang & Devitt, 2026). Likewise, collaborative online and immersive learning studies report that social presence, peer interaction, and a sense of community improve when platforms and activities are intentionally designed around collaborative participation rather than simple co-presence (Li et al., 2024; Timonen & Ruokamo, 2021). Task-level evidence points in the same direction: asynchronous discussion forums, collaborative document creation, group case analysis, debate, and reflective journals are effective because they explicitly organize peer interaction, feedback, and joint knowledge construction (Nagalla et al., 2025). Similar findings from project-based and digital collaboration research show that communication and collaboration improve when teachers act as facilitators, scaffold participation, and structure authentic group problem solving (Sah et al., 2024; Hazrat et al., 2023; Herman et al., 2025).

Overall, these results support the interpretation that DTT is better understood as an enabling environment than as a direct cause of higher-order and interpersonal competencies. Reflection, abstraction, discussion, peer feedback, and collaborative task design appear more central than technological activity alone in explaining why some students report stronger critical thinking, creativity, or collaboration (Manju, 2026; Dillard et al., 2024; Ramaila & Molwele, 2022; Simon & Mutmainah, 2025).

4.4 Theoretical Implication

The findings provide a nuanced interpretation of Kolb's experiential learning framework in DTT-supported learning. Although digital twins can create highly interactive and authentic learning environments, the results suggest that technological engagement alone does not uniformly translate into stronger 21st-century competencies. This is consistent with research positioning DTT as a pedagogical infrastructure that provides opportunities for interaction, experimentation, and access to realistic systems, while the quality of learning depends on how these opportunities are designed, scaffolded, and interpreted (Chamorro-Atalaya et al., 2024; Pathak & Upadhyay, 2024; Hazrat et al., 2023). The observed relationships further suggest that Reflective Observation and Abstract Conceptualization may be particularly important in transforming technological experiences into meaningful learning outcomes. Within Kolb's framework, reflection enables learners to examine their experiences, while conceptualization allows them to organize those experiences into principles and frameworks that can guide future action (Kee et al., 2023; Dillard et al., 2024). This interpretation is consistent with technology-enhanced learning research showing that critical thinking and other higher-order competencies are more likely to develop when digital activities incorporate inquiry, reflection, problem solving, and authentic tasks rather than passive technological interaction (Manju, 2026; Diyal, 2024; O'Connor et al., 2022).

The DTT literature provides a further explanation for this pattern. Digital twins can simulate realistic systems, allow learners to manipulate variables, observe consequences, and practice decision-making in relatively safe environments, thereby supporting authentic engagement and experimentation (Ortiz et al., 2025; Pathak & Upadhyay, 2024; Speicher et al., 2026). However, their educational impact remains dependent on teacher facilitation, pedagogical design, infrastructure, and integration with broader learning activities (Chamorro-Atalaya et al., 2024; Hazrat et al., 2023). Similar evidence from immersive learning indicates that different digital environments support different combinations of critical thinking, creativity, communication, and collaboration, rather than producing uniform effects across competency domains (Damaševičius & Sidekerskienė, 2024; Kee et al., 2023).

Overall, the findings support a pedagogically mediated interpretation of DTT. Digital twins appear to function most effectively as enabling environments that provide realistic and manipulable experiences, while higher-order competencies emerge through the deliberate integration of reflection, conceptualization, inquiry, collaboration, and feedback. Thus, the results extend Kolb's framework by suggesting that in DTT-supported learning, technological affordances may create the conditions for experiential learning, but pedagogical mediation determines how effectively those experiences are transformed into 21st-century competencies.

4.5 Practical Implications

The findings suggest that DTT activities should be designed as complete experiential learning sequences rather than isolated simulation or experimentation tasks. Consistent with Kolb's framework, effective DTT learning should connect concrete experience, reflection, abstract conceptualization, and active experimentation (Dillard et al., 2024; O'Connor et al., 2022). Thus, educators should embed DTT within coherent instructional designs rather than treating the technology itself as the primary source of learning.

A practical DTT sequence may begin with an authentic system problem, followed by opportunities for students to manipulate variables, observe outcomes, and monitor system behavior. Students should then be guided to document unexpected results, reflect on discrepancies between predictions and observations, and connect their experiences to relevant disciplinary concepts (Kee et al., 2023; Pathak & Upadhyay, 2024; Ortiz et al., 2025). The sequence should culminate in testing revised explanations or solutions, allowing students to apply and refine their understanding through feedback (Dillard et al., 2024).

Because the findings suggest that reflection and conceptual processing may be particularly relevant to higher-order competencies, DTT activities should incorporate structured reflection, debriefing, and conceptual explanation rather than relying primarily on interaction with the simulation. Similarly, communication and collaboration should be deliberately supported through group investigation, peer discussion, shared decision-making, and collaborative problem solving, as these competencies are unlikely to develop automatically through technological participation alone (Timonen & Ruokamo, 2021; Li et al., 2024).

These recommendations should be interpreted as pedagogical implications rather than evidence of causality. Further experimental and longitudinal research is needed to determine whether fully sequenced experiential DTT designs

produce stronger improvements in critical thinking, creativity, communication, and collaboration than simulation-focused approaches (Chamorro-Atalaya et al., 2024; Hazrat et al., 2023; Pathak & Upadhyay, 2024). Overall, the evidence supports DTT as an enabling environment whose educational value is maximized when authentic interaction is deliberately integrated with reflection, conceptualization, experimentation, and structured social learning.

5. Limitations and Future Research

Several limitations should be considered. First, the study used self-reported perceptions for both DTT experiences and 21st-century competencies. Such measures can provide useful information about learners' experiences but may not correspond directly to demonstrated performance. Future studies should incorporate objective or performance-based measures of critical thinking, communication, collaboration, and creativity.

Second, the cross-sectional descriptive-correlational design prevents causal inference. The findings cannot establish that DTT caused the development of any competency. Longitudinal and quasi-experimental designs, including pretest-posttest comparisons and appropriate comparison groups, would provide stronger evidence of educational effects.

Third, purposive sampling from one vocational institution limits generalizability. Multi-institutional studies with larger and more diverse samples would help determine whether the observed patterns are robust across disciplines, regions, and educational contexts.

Fourth, although the questionnaire demonstrated preliminary content validity and internal consistency, more extensive psychometric validation is warranted. Future studies should report construct-level reliability and examine the factor structure of the instrument, preferably using independent samples.

Fifth, the analysis involved multiple pairwise correlations. Future studies should pre-specify primary hypotheses and use appropriate multiplicity control. Larger samples would also permit multivariable models that can examine whether demographic characteristics or technology proficiency explain variation in the observed relationships.

Finally, future research should provide detailed descriptions of the DTT learning environment and distinguish genuine digital twin systems from conventional simulation or immersive technologies. Comparative studies could examine DTT against conventional simulation, virtual reality, or other technology-supported approaches.

6. Conclusion

This study found that students reported highly positive perceptions of DTT-supported learning across all four dimensions of Kolb's experiential learning cycle. However, the relationships between experiential learning dimensions and perceived 21st-century competencies were weak and selective. Critical thinking showed weak associations with Concrete Experience, Reflective Observation, and Abstract Conceptualization; creativity was weakly associated with Concrete Experience and Abstract Conceptualization; collaboration was weakly associated with Concrete Experience; and communication showed no statistically significant associations.

The findings therefore do not establish that DTT causes 21st-century skill development. Rather, they suggest that students' perceptions of particular experiential learning processes are modestly related to their perceptions of selected competencies. The contrast between the high rating for Active Experimentation and its lack of significant association with critical thinking and creativity is particularly noteworthy. It suggests that technological interaction and experimentation may need to be accompanied by reflection, conceptual processing, and intentionally designed social learning activities if DTT is to contribute meaningfully to broader competency development.

The principal implication is that DTT should be understood as a pedagogical environment whose educational value depends partly on instructional design. Future experimental and longitudinal research using objective competency assessments is needed to determine whether the patterns identified here translate into measurable improvements in student performance.

7. Recommendations

1. Design DTT activities around the complete experiential learning cycle, incorporating experience, reflection, conceptual interpretation, and subsequent experimentation.
2. Integrate structured reflection prompts, concept mapping, guided discussion, and evidence-based explanation into DTT activities.
3. Use collaborative tasks, peer feedback, group investigation, and argumentation when communication and collaboration are intended learning outcomes.
4. Validate the present questionnaire more extensively and, where possible, combine self-report measures with authentic performance assessments.

5. Conduct longitudinal or quasi-experimental studies with pretest-posttest designs and comparison groups to examine actual changes attributable to DTT-supported instruction.
6. Replicate the study across multiple institutions and disciplines and report the characteristics of the DTT platforms and learning tasks in sufficient detail to permit replication.

Author Contributions

Yi Yangjing: conceptualization, methodology, data collection, and original draft preparation. Immanuel T. San Diego: supervision, methodological review, interpretation, and manuscript revision. Both authors approved the final manuscript.

Data Availability Statement

The dataset is not publicly deposited in the present manuscript. Data availability should be stated according to institutional ethics and data-governance requirements.

Conflict of Interest

The authors declare no conflict of interest.

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