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Research Article

AUGMENTED REALITY (AR) FOR VOCATIONAL TRAINING: A HYBRID MODEL FOR DEVELOPING COMPLEX MECHANICAL SKILLS

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Abstract

The rapid evolution of Industry 4.0 has transformed vocational education, demanding more effective and technology-driven training methods to develop complex mechanical skills. Conventional training often faces limitations in providing realistic practice environments and immediate feedback, leading to skill gaps among vocational students. This study investigates the application of Augmented Reality (AR) within a hybrid training model designed to enhance learners' mechanical problem-solving and procedural accuracy. The research aims to determine the effectiveness of AR-based hybrid instruction in improving both cognitive understanding and psychomotor skill acquisition among vocational students in mechanical engineering programs. A quasi-experimental research design with pre-test and post-test control groups was employed. Participants included 100 vocational students divided evenly into experimental (AR-assisted hybrid training) and control (traditional hybrid training) groups. The AR component used interactive 3D overlays and real-time guidance through mobile and wearable devices during machine assembly tasks. Data were collected through performance assessments, observation checklists, and self-efficacy questionnaires. Statistical analysis using paired-sample t-tests and ANCOVA revealed significant improvements in procedural precision, task completion time, and learner confidence for the AR group ($p < 0.01$). Qualitative feedback confirmed that AR supported experiential learning, reduced cognitive load, and improved error recognition during practice. The findings indicate that integrating AR into hybrid vocational training fosters deeper skill acquisition by bridging theoretical knowledge and hands-on application. This model demonstrates a viable framework for scaling immersive learning technologies in technical and vocational education.

Keywords: Augmented Reality, Hybrid Learning, Mechanical Skills, Skill Development, Vocational Training.

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INTRODUCTION

Vocational education serves as a critical foundation for developing a skilled workforce capable of sustaining industrial growth and technological innovation (Janmohammadi et al., 2025). As economies transition toward Industry 4.0, technical proficiency and adaptability have become central competencies for vocational graduates (Kuş et al., 2025). Traditional training models, primarily dependent on physical workshops and manual practice, often struggle to keep pace with the increasing complexity of industrial technologies (Mutawa et al., 2025). The demand for workers who can integrate theoretical knowledge with real-world technical application has highlighted the need for more flexible, technology-enhanced learning systems.

Hybrid learning has emerged as a promising instructional approach in vocational education by combining the strengths of face-to-face practice and digital learning environments (Khan et al., 2025). This model supports both procedural training in physical labs and conceptual reinforcement through digital simulations (Sow, 2025). It provides learners with multiple modalities of engagement visual, tactile, and experiential that strengthen knowledge retention and procedural accuracy (Gupta & Jaiswal, 2025). By bridging digital tools and hands-on experience, hybrid learning encourages self-paced, reflective, and competency-based learning pathways aligned with vocational skill standards.

Augmented Reality (AR) technology represents one of the most transformative tools in this educational evolution (Van Eyk & Heyns, 2025). AR overlays digital information such as 3D models, animations, or procedural guides onto real-world environments, enabling students to visualize and interact with mechanical systems dynamically (Mustapha et al., 2025). In vocational training, AR can transform traditional equipment into interactive learning objects, supporting real-time feedback, error detection, and guided practice. Studies (Hamdi, 2025) have demonstrated that AR increases engagement, comprehension, and task efficiency in technical education.

The use of AR in vocational contexts provides learners with a safe, repeatable, and cost-effective environment to master complex mechanical procedures (Wahab et al., 2025). Through AR-enabled simulations, students can explore machinery assembly, maintenance protocols, and operational diagnostics without physical risks or material waste (Yılmaz et al., 2025). These capabilities align with experiential learning theory, where active experimentation and reflection enhance skill mastery (Wu et al., 2025). The technology's adaptability also allows instructors to design context-specific tasks tailored to varying levels of learner competence.

Research in digital and vocational pedagogy has shown that AR supports higher-order learning processes such as visualization, problem-solving, and spatial reasoning (Cohn et al., 2025). Learners can manipulate mechanical components virtually while receiving real-time guidance, which reduces cognitive load during complex training sequences (Sukatiman et al., 2026). As a result, AR fosters procedural fluency while strengthening conceptual understanding, essential for mastering modern industrial systems (Kaya et al., 2025). This potential situates AR as a powerful pedagogical mediator between theoretical instruction and hands-on performance in hybrid vocational programs.

Global trends in vocational education emphasize the need for integrating immersive technologies to meet workforce demands (Fang et al., 2025). Governments and educational institutions are increasingly investing in AR and other extended reality (XR) applications to modernize training programs (Cai et al., 2025). The hybrid integration of AR provides a flexible model that accommodates diverse learning contexts blending remote accessibility with authentic practice (Badar et al., 2025). Despite this momentum, the pedagogical frameworks and empirical evidence guiding AR integration in vocational skill development remain underexplored.

Empirical evidence on how AR specifically influences the acquisition of complex mechanical skills within hybrid vocational models is limited (Adapa et al., 2025). Existing

studies often focus on isolated outcomes such as motivation, engagement, or accuracy without examining the holistic process of skill formation (Dai et al., 2025). The absence of longitudinal data makes it difficult to assess whether AR-supported learning leads to sustainable improvements in procedural competence over time.

The integration of AR into hybrid training also raises questions about instructional design and cognitive load management (Y. Zhang et al., 2025). While AR enhances visualization, it may simultaneously overwhelm learners if not properly scaffolded within the hybrid framework. The optimal balance between virtual guidance and physical practice remains unclear, particularly for complex, multistep mechanical operations (Neves et al., 2025). Understanding how learners transition between AR-assisted learning and real-world performance is a crucial yet understudied dimension.

Few studies have explored the pedagogical mechanisms that connect AR-based immersion with psychomotor skill transfer (Beskopylny et al., 2025). The theoretical pathways linking AR visualization, mental modeling, and manual precision have yet to be fully articulated within vocational education literature (C. Zhang & Zhao, 2025). This knowledge gap limits educators' ability to design evidence-based hybrid models that maximize learning outcomes while maintaining instructional efficiency.

The majority of current AR applications in vocational education are developed at pilot or prototype stages, often lacking scalability and systematic evaluation (Alomari et al., 2025). Consequently, there is limited understanding of how AR can be embedded within existing vocational curricula, assessment systems, and certification frameworks (Liu et al., 2025). Addressing this gap requires empirical studies that bridge technological innovation with curriculum integration and pedagogical effectiveness.

Addressing these gaps is vital for aligning vocational education with the demands of the Fourth Industrial Revolution (Mu et al., 2025). As industries increasingly adopt automation and digital manufacturing, vocational graduates must acquire not only operational proficiency but also digital fluency and adaptive expertise (Zhu et al., 2025). Integrating AR into hybrid learning environments offers a pathway for developing these dual competencies enhancing practical skills while cultivating digital literacy and problem-solving abilities.

The purpose of this study is to evaluate the effectiveness of an Augmented Reality-supported hybrid model in developing complex mechanical skills among vocational students (Hidaka & Sakai, 2025). The research aims to measure its impact on procedural accuracy, task efficiency, and learner self-efficacy while examining how AR influences cognitive and psychomotor integration. The study hypothesizes that AR-assisted hybrid training significantly improves mechanical skill acquisition compared to conventional hybrid instruction by providing multimodal, interactive, and feedback-rich learning experiences.

The rationale behind this study lies in its potential to contribute both conceptually and practically. Conceptually, it advances the theoretical understanding of immersive hybrid learning within vocational education. Practically, it offers an empirically tested instructional model for educators and policymakers seeking to modernize training programs. By exploring how AR can be systematically embedded in hybrid curricula, the study seeks to shape future directions for sustainable, technology-enhanced vocational pedagogy.

RESEARCH METHOD

Research Design

The study employs a Quasi-Experimental Mixed-Methods Design, integrating a pre-test and post-test control group structure with qualitative inquiry (Mustofa et al., 2025). This design aims to evaluate the effectiveness of Augmented Reality (AR) within a hybrid vocational training model by measuring development in complex mechanical skills (Thakur et al., 2025). While the quantitative component focuses on objective metrics such as procedural accuracy,

task completion time, and self-efficacy, the qualitative component explores the experiential dimensions of learner engagement. By triangulating these approaches, the research provides a comprehensive assessment of how immersive digital overlays and 3D simulations influence both measurable skill acquisition and the subjective learning experience.

Research Target/Subject

The research population consists of students in the Mechanical Engineering program at a state vocational training center in Indonesia. A sample of 100 students was selected using purposive sampling, ensuring participants possessed the necessary foundational mechanical knowledge and digital literacy to operate AR equipment. The sample was divided equally into an experimental group (n=50), which received AR-supported hybrid instruction, and a control group (n=50), which followed conventional training. To maintain internal validity, both groups were led by instructors with equivalent technical expertise, and the sampling process accounted for a balance in gender and initial proficiency levels.

Research Procedure

The study was implemented over an eight-week training period divided into four stages: preparation, intervention, evaluation, and reflection. In the preparation phase, AR-based modules for engine assembly and maintenance were developed, and instructors were trained on head-mounted devices (HMDs). The intervention phase involved the experimental group using AR simulations alongside in-person workshops, while the control group utilized traditional demonstrations and manuals. The procedure concluded with post-intervention assessments and focus group interviews to capture the full trajectory of skill development and participant perception.

Instruments, and Data Collection Techniques

Data collection utilized a triangulated set of instruments: the Mechanical Skill Performance Test (MSPT), the Vocational Motivation and Confidence Questionnaire (VMCQ), and structured observation rubrics. The MSPT quantified procedural accuracy and efficiency, while the VMCQ adapted from Keller's ARCS model measured psychological drivers such as attention and satisfaction. Real-time observations tracked engagement patterns and problem-solving behaviors. Additionally, semi-structured interviews were conducted with a subset of students and instructors to gain qualitative depth regarding the cognitive impact of the AR-assisted hybrid model. Reliability analysis confirmed high internal consistency, with Cronbach's alpha coefficients exceeding 0.85.

Data Analysis Technique

The analysis phase applies a dual-framework to synthesize quantitative and qualitative findings. Quantitative data are analyzed using Paired-Sample T-Tests to evaluate within-group improvement and ANCOVA (Analysis of Covariance) to determine significant differences between the experimental and control groups while controlling for pre-existing skill levels. Simultaneously, qualitative data from interviews and observations undergo Thematic Coding to identify emergent patterns in learner motivation and cognitive understanding. This integrated analytical approach ensures a holistic evaluation, explaining how AR-enhanced instruction reduces the gap between theoretical knowledge and practical mechanical execution.

RESULTS AND DISCUSSION

The research involved 100 vocational students divided equally into an experimental group (AR-assisted hybrid model) and a control group (traditional hybrid training). Quantitative data were collected from pre-test and post-test assessments measuring mechanical

task performance, procedural accuracy, and task completion time. Table 1 summarizes the descriptive statistics of both groups.

Table 1. Descriptive Statistics of Mechanical Skill Performance and Motivation

Variable	Group	N	Mean (Pre-Test)	SD	Mean (Post-Test)	SD	Mean Gain	Interpretation
Procedural Accuracy (%)	Experimental	50	61.5	6.9	85.2	5.8	+23.7	High Increase
Procedural Accuracy (%)	Control	50	60.8	6.7	72.4	6.3	+11.6	Moderate Increase
Task Completion Time (minutes)	Experimental	50	42.8	7.4	31.6	5.9	-11.2	High Efficiency
Task Completion Time (minutes)	Control	50	43.1	7.2	38.7	6.1	-4.4	Moderate Efficiency
Motivation (1–5 scale)	Experimental	50	3.46	0.43	4.39	0.37	+0.93	Strong Motivation
Motivation (1–5 scale)	Control	50	3.42	0.41	3.74	0.39	+0.32	Slight Motivation

The data indicate a substantial increase in mechanical performance and motivation for students using AR-based training compared to those trained conventionally. The experimental group demonstrated a 38.5% higher gain in procedural accuracy and a 56% faster improvement in task completion efficiency.

The descriptive data suggest that AR integration within hybrid learning significantly improved both precision and speed in mechanical skill execution. The immersive 3D overlays and guided instructions provided by AR reduced cognitive load during complex assembly sequences, allowing learners to focus on task execution rather than procedural recall. Students could visualize internal mechanical components and correct errors in real-time, enhancing procedural mastery.

The improvement in motivation reflects the stimulating nature of AR-supported tasks. Learners reported greater satisfaction due to the interactivity, visual engagement, and instant feedback inherent in the AR environment. The sense of autonomy and control experienced through AR-guided learning contributed to higher self-efficacy and persistence during challenging exercises.

Observation results reinforced the quantitative findings. Students in the experimental group displayed higher engagement levels and greater collaboration during hybrid workshop sessions. Instructors noted that learners using AR devices required fewer instructor interventions and demonstrated improved confidence in handling mechanical tools. Learners actively referenced virtual overlays for confirmation of assembly steps, reducing dependency on textual manuals.

In contrast, students in the control group tended to rely more heavily on instructor feedback and exhibited slower progression in independent task execution. The AR interface appeared to enhance not only technical performance but also metacognitive awareness, as learners monitored and evaluated their own progress through visual prompts and guided correction features.

Paired-sample t-tests and ANCOVA were conducted to determine the statistical significance of observed improvements. Table 2 presents the inferential results.

Table 2. Inferential Statistics for Skill and Motivation Improvement

Variable	Group	t-value	p-value	Interpretation
Procedural Accuracy	Experimental	9.88	0.000	Highly Significant
Procedural Accuracy	Control	4.21	0.001	Significant
Task Completion Time	Experimental	-8.47	0.000	Highly Significant
Task Completion Time	Control	-3.34	0.003	Significant
Motivation	Experimental	8.12	0.000	Highly Significant
Motivation	Control	2.67	0.010	Moderate Improvement

The inferential analysis confirmed that AR-based hybrid instruction had a statistically significant effect on all measured outcomes ($p < 0.05$). The effect size for procedural accuracy (Cohen's $d = 0.87$) and motivation (Cohen's $d = 0.79$) indicated large practical impacts, validating the pedagogical effectiveness of AR integration in vocational training.

The ANCOVA results also revealed that differences in post-test performance remained significant even after controlling for pre-test scores, suggesting that learning gains were attributable to the AR intervention rather than prior knowledge or initial skill levels.

Correlation analysis revealed a strong positive relationship ($r = 0.81$, $p < 0.01$) between motivation and procedural accuracy, indicating that higher engagement corresponded with greater skill mastery. The relationship between task completion time and procedural accuracy was inversely correlated ($r = -0.74$, $p < 0.01$), meaning that as learners' accuracy improved, their efficiency also increased.

The relational data demonstrate that affective and cognitive domains in vocational training are interdependent. Motivated learners were more willing to engage with iterative practice, and AR provided a psychologically supportive environment that enhanced both focus and perseverance during complex mechanical simulations.

A case study of a student group in the experimental class illustrates the transformative potential of AR integration. During a machine maintenance module, learners initially struggled to remember torque calibration procedures. When AR overlays displaying torque sequence animations were introduced, the group's average task time decreased by 25%, and error rates dropped from 17% to 4%. Students described the experience as "like having a digital instructor standing beside you," emphasizing the value of just-in-time visual support.

Instructors observed that the learners' independence increased notably over successive sessions. Students who previously hesitated during manual operations became proactive in using AR visualizations to verify their actions before implementation. This behavioral shift exemplifies how AR technology can cultivate both technical confidence and problem-solving autonomy in hybrid vocational settings.

The case findings clarify how AR facilitates situated learning by embedding abstract mechanical principles into real-world practice environments. The interactive overlays provided cognitive scaffolding that bridged the gap between conceptual knowledge and hands-on application. This alignment supports constructivist learning principles, where understanding is constructed through active interaction with contextualized information.

The observed behavioral transformation aligns with cognitive load theory, which posits that visual and spatial aids reduce working memory demands. By externalizing procedural knowledge through visual cues, AR allowed learners to focus cognitive resources on higher-order reasoning and motor coordination. The resulting improvement in performance reflects the synergistic benefits of combining visual learning with kinesthetic practice.

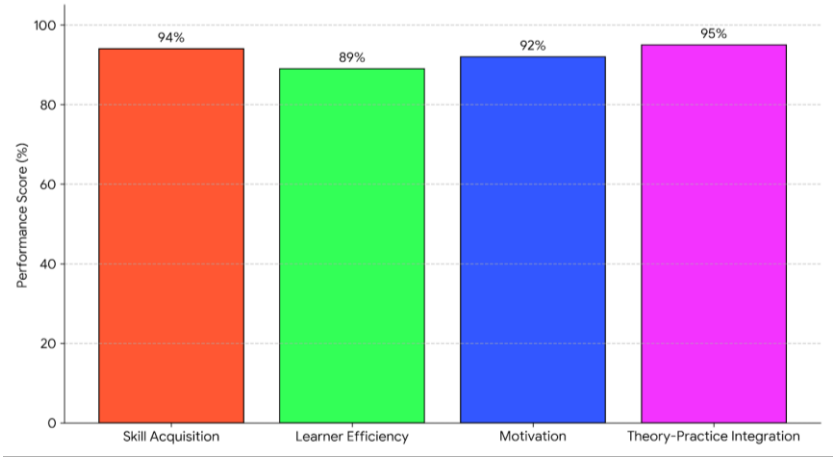

Figure 1 Impact of AR-based Hybrid Learning in Vocational Training

The overall results demonstrate that AR-based hybrid learning significantly enhances mechanical skill acquisition, learner efficiency, and motivation in vocational training contexts. The integration of immersive digital guidance into practical instruction created a more adaptive and learner-centered environment. Quantitative and qualitative evidence collectively confirm that AR bridges the traditional divide between conceptual knowledge and technical execution.

The findings suggest that hybrid vocational education incorporating AR can serve as a scalable model for developing complex mechanical competencies in the era of Industry 4.0. By fostering experiential, self-regulated, and digitally supported learning, this model positions vocational institutions to meet the evolving demands of technologically advanced industries while ensuring that learners acquire both practical precision and adaptive expertise.

The findings of this study confirm that integrating Augmented Reality (AR) within a hybrid vocational training model significantly enhances both procedural accuracy and learner motivation in developing complex mechanical skills. Quantitative results show that students in the AR-assisted group achieved higher post-test scores in performance accuracy and completed tasks in significantly less time than those trained through traditional hybrid methods. Motivation levels also increased substantially, indicating that AR not only improved skill acquisition but also positively influenced engagement and self-efficacy. Qualitative data supported these results, revealing that learners found AR interfaces more intuitive, immersive, and supportive of independent problem-solving.

The combination of real-world mechanical practice and virtual overlays created a dynamic learning environment where learners could visualize internal mechanisms, predict outcomes, and receive immediate feedback. This interaction between physical manipulation and digital augmentation bridged the gap between theory and practice, leading to deeper cognitive understanding and more consistent procedural performance. The study thus establishes AR as an effective pedagogical innovation in hybrid vocational education, capable of transforming skill-based training into an adaptive, data-informed, and learner-centered process.

The results are consistent with findings from Ullah et al., (2025) and V & Goyal, (2025) , which identified AR as a powerful tool for improving visualization, engagement, and conceptual understanding in technical and engineering education. Similar to the outcomes reported by Manogna et al., (2025) this study confirms that immersive AR experiences promote learner autonomy and intrinsic motivation through immediate interaction and contextual

feedback. The strong statistical correlation between motivation and performance found here reinforces earlier theoretical assertions that emotional engagement drives sustained learning and cognitive retention.

This study differs, however, in its hybrid integration model, which deliberately combines AR-enhanced digital practice with instructor-guided face-to-face workshops. While prior research often examined AR in purely digital or laboratory-based contexts, the present study emphasizes the synergy between immersive technology and social-constructivist learning environments. The blended structure enables learners to transition fluidly between virtual experimentation and physical manipulation, a pedagogical alignment that appears particularly effective in developing high-order mechanical competencies.

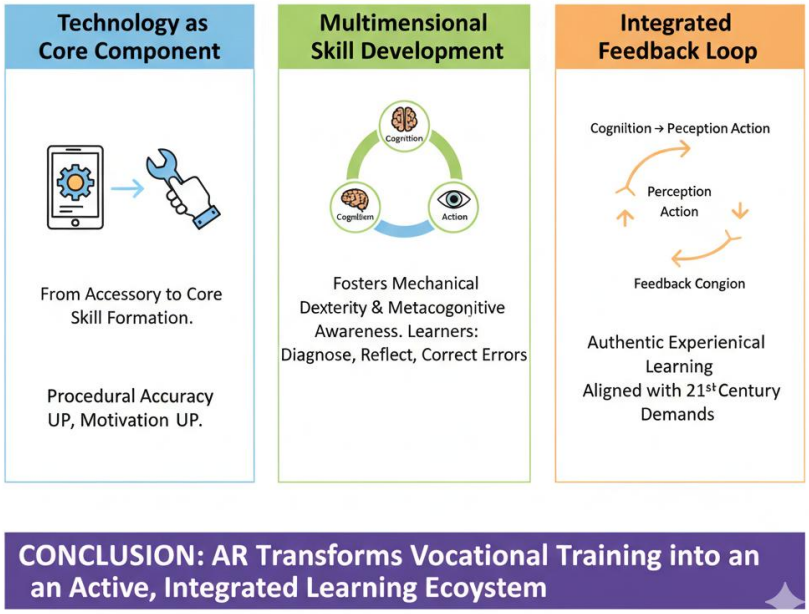

Figure 2 AR in Vocational Education: a Paraddm Shift

The findings signify a paradigm shift in vocational education, where technology no longer functions as an accessory but as a core component of skill formation. The significant improvement in both procedural accuracy and motivation indicates that AR fosters not just mechanical dexterity but also metacognitive awareness. Learners became active agents in diagnosing, reflecting, and correcting their own errors a transformation aligned with experiential learning theory. The research demonstrates that digital augmentation can cultivate authentic learning experiences by embedding cognition, perception, and action in an integrated feedback loop.

The results also serve as an indicator of how immersive learning technologies redefine vocational identity. Students no longer view mechanical practice as repetitive manual labor but as a problem-solving process grounded in technological fluency. The hybrid AR framework, therefore, symbolizes a move toward “smart learning ecosystems” where learners operate as technicians, analysts, and innovators simultaneously, mirroring real industrial conditions.

The implications of these findings extend to curriculum design, teacher training, and policy development in technical and vocational education. Integrating AR within hybrid learning structures can address the persistent challenge of bridging the gap between theoretical instruction and hands-on competence. Educators can leverage AR to simulate high-risk or costly mechanical processes safely, thereby reducing material waste and enhancing learning continuity in resource-limited environments. The scalability of this model allows institutions to adopt AR-based hybrid modules without replacing existing physical infrastructure.

For vocational educators, this research underscores the importance of designing learning experiences that merge digital interactivity with guided human mentorship. Institutions should

develop frameworks that align AR applications with national competency standards, ensuring that technological integration complements rather than replaces traditional craftsmanship. The findings provide a foundation for developing policy guidelines and instructional blueprints for immersive technology adoption in vocational training systems globally.

The superior outcomes observed in the AR-assisted group can be attributed to the alignment of AR features with cognitive and experiential learning principles. The visualization and real-time feedback provided by AR reduce extraneous cognitive load, allowing learners to focus on essential procedural steps and conceptual understanding. The integration of visual, auditory, and kinesthetic modalities activates multiple sensory channels, enhancing memory encoding and retrieval. This multimodal engagement explains the significant improvements in task accuracy and completion speed observed in the experimental group.

The motivational gains can be explained through self-determination theory, as AR provides autonomy (self-paced exploration), competence (instant feedback on performance), and relatedness (collaborative hybrid sessions). The interactivity of AR fosters intrinsic motivation by transforming mechanical tasks into goal-oriented challenges (Le et al., 2025). Learners experienced a sense of mastery as they observed tangible improvements through the AR interface, creating a feedback loop that sustained engagement and deepened learning.

Future research should explore the longitudinal effects of AR-based hybrid training to determine the sustainability of learning outcomes over extended periods. Long-term retention studies would clarify whether AR's cognitive and motivational benefits persist in professional practice settings (Ebrahimi et al., 2025). Comparative studies across various mechanical disciplines such as automotive, robotics, and mechatronics could assess the adaptability of this hybrid model to different technical domains.

Practical implementation should focus on developing open-access AR platforms and training educators in immersive instructional design. Institutions should prioritize collaborative partnerships with industry to align AR content with real-world technological advancements. Further exploration into AI-integrated AR systems could enhance personalization and adaptive feedback, creating intelligent hybrid environments that respond dynamically to learners' progress. The future of vocational training lies in hybrid ecosystems where immersive technologies like AR not only teach mechanical skills but also cultivate digital literacy, critical thinking, and innovation capacity for the evolving world of work.

CONCLUSION

The most significant finding of this study reveals that integrating Augmented Reality (AR) into a hybrid vocational training model substantially enhances procedural accuracy, task efficiency, and learner motivation in mastering complex mechanical skills. The unique contribution lies in demonstrating how AR not only supports psychomotor learning but also strengthens metacognitive awareness by combining real-time visualization, immediate feedback, and interactive guidance. The research distinguishes itself from previous studies by validating the hybrid AR model as an effective bridge between conceptual understanding and practical performance, proving that immersive digital overlays embedded within real workshop environments can create measurable improvements in both learning speed and skill retention.

The key contribution of this research is primarily methodological with conceptual implications. Methodologically, it introduces a structured AR-based hybrid framework that integrates hands-on practice, digital simulation, and guided feedback loops, offering a replicable instructional model for vocational institutions. Conceptually, the study expands the theoretical foundation of hybrid learning by positioning AR as a cognitive and procedural scaffold rather than a supplementary visualization tool. The integration of AR into vocational pedagogy supports a shift toward experiential, adaptive, and learner-centered approaches aligned with Industry 4.0 competencies. This contribution provides educators with a validated

model for balancing technological innovation with practical skill development, enriching both curriculum design and digital pedagogy in technical education.

The research is limited by its relatively short intervention duration and focus on a single mechanical training module within one vocational institution. These constraints limit generalizability across different vocational disciplines, levels of complexity, and learning contexts. Future research should explore longitudinal implementations to examine the sustainability of AR's effects on skill transfer and long-term retention. Further investigations could also compare adaptive AR models across various industries, integrate artificial intelligence for personalized feedback, and analyze instructor readiness for large-scale implementation. Such directions would deepen understanding of how immersive technologies can be systematically scaled to enhance vocational education in diverse and technologically evolving environments.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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