Enhancing Automotive Repair Competencies through Augmented Reality: An Empirical Evaluation of Efficacy in Vocational Training

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Abstract

The rapid integration of complex electronic and mechanical systems in modern vehicles has rendered traditional instructional methods in Technical and Vocational Education and Training (TVET) increasingly inadequate. Augmented Reality (AR) has emerged as a transformative pedagogical tool capable of bridging the gap between theoretical knowledge and practical application. This study evaluates the efficacy of AR interventions in vocational training for automotive repair. Using a quasi-experimental mixed-methods design, 120 vocational students were divided into a control group utilizing traditional 2D service manuals and an experimental group utilizing wearable AR headsets (Microsoft HoloLens 2) providing 3D holographic overlays and real-time guidance. Participants were evaluated on a complex procedural task: diagnosing and repairing a front-wheel-drive powertrain. Quantitative results indicate that the AR-assisted group demonstrated a significantly higher procedural accuracy rate and a 24% reduction in task completion time compared to the control group. Furthermore, cognitive load assessments utilizing the NASA-TLX scale revealed a reduction in extraneous cognitive load among AR users. Qualitative feedback highlighted enhanced learner motivation and spatial understanding, though limitations regarding hardware fatigue and initial deployment costs were noted. The findings suggest that AR is a highly efficacious tool for procedural skill acquisition in automotive vocational training. This paper provides actionable insights for curriculum designers and aligns with the technology and education tracks of ICCMETS 2026.

Keywords: Augmented Reality, Vocational Training, Automotive Repair, Efficacy, Immersive Learning, Technical Education.

1. Introduction

The automotive industry is currently undergoing a paradigm shift, transitioning from purely mechanical engineering to complex, highly integrated mechatronic and software-driven systems. As vehicles increasingly incorporate Internet of Things (IoT) sensors, hybrid powertrains, and advanced driver-assistance systems (ADAS), the cognitive and technical demands placed on automotive technicians have surged exponentially (Marope, Chakroun, & Holmes, 2023). Consequently, Technical and Vocational Education and Training (TVET) institutions face the daunting challenge of updating their pedagogical frameworks to produce a workforce capable of navigating these modern complexities.

Traditional vocational training heavily relies on 2D service manuals, static diagrams, and master-apprentice observational models. However, translating two-dimensional schematics into three-dimensional, hands-on mechanical tasks imposes a high cognitive burden on learners, frequently resulting in procedural errors and prolonged learning curves (Muslim, 2026). To mitigate these challenges, educational technologists are increasingly turning toward immersive technologies, specifically Augmented Reality (AR). Unlike Virtual Reality (VR), which fully isolates the user in a digital environment, AR seamlessly superimposes digital information—such as 3D models, procedural animations, and diagnostic data—onto the user's real-world physical environment (Radianti et al., 2020).

Despite the theoretical promise of AR in educational settings, empirical evidence evaluating its efficacy in specific, high-stakes vocational contexts like automotive repair remains fragmented.

Aligning with the core themes of the ICCMETS 2026 conference—which emphasize the intersection of Education and Technology—this study aims to rigorously quantify the instructional efficacy of AR tools in automotive vocational training.

1.1 Objectives and Research Questions

The primary objective of this research is to evaluate the impact of AR-based instructional overlays on the acquisition of practical skills in automotive repair. The study is guided by the following research questions:

How does the use of AR impact the procedural accuracy and task completion time of students performing complex automotive repairs compared to traditional 2D manuals?

What effect does AR-assisted training have on the cognitive load of vocational learners?

How do students perceive the usability and motivational aspects of AR technology in their training environment?

2. Literature Review

2.1 The Evolution of TVET Pedagogies

Vocational training has historically relied on the cognitive apprenticeship model, where learners observe and mimic the actions of an expert. While effective for repetitive mechanical tasks, this model falters when addressing "invisible" systems, such as electrical workflows or internal fluid dynamics. According to Ndiwu and Athumani (2026), the gap between theoretical classroom instruction and practical workshop application is a primary contributor to high attrition rates in engineering and vocational programs.

2.2 Immersive Technologies in Skill Acquisition

The integration of VR and AR in vocational training has demonstrated significant potential in reducing the aforementioned skills gap. Liu, Zhan, and Zhao (2023) posit that immersive technologies facilitate a "situated learning" environment, allowing trainees to practice complex tasks safely while receiving real-time contextual feedback. While VR is highly effective for risk-free simulations (e.g., aviation or high-voltage electrical work), AR adds unique value by overlaying digital guidance directly onto the physical machinery being repaired, eliminating the "split-attention effect" inherent in consulting external manuals (Bicalho et al., 2023).

2.3 Efficacy of AR in Automotive Maintenance

Earlier studies in automotive AR applications focused primarily on basic maintenance tasks. Quevedo et al. (2017) demonstrated that AR-assisted maintenance modules enhanced learner accuracy in basic engine assembly. More recently, Muslim (2026) conducted a case study on front-wheel-drive powertrain learning, concluding that spatial reasoning and dynamic visualization provided by AR significantly improved technical performance. However, existing literature frequently cites limitations such as tracking errors, device ergonomics, and the high cost of implementation. This study builds upon prior research by utilizing the latest generation of spatial computing hardware to provide a robust empirical analysis of AR's efficacy.

3. Theoretical Framework

This study is anchored in two foundational educational theories:

Cognitive Load Theory (CLT): Proposed by John Sweller, CLT suggests that human working memory is limited. Traditional training methods require learners to constantly shift their attention between a repair manual and the physical vehicle, generating "extraneous cognitive load." By spatially aligning digital instructions with the physical task, AR theoretically reduces this extraneous load, freeing cognitive resources for schema acquisition and actual problem-solving (Radianti et al., 2020).

Experiential Learning Theory: Kolb's theory emphasizes learning through doing. AR enhances this process by providing immediate, visually intuitive feedback during the "Active Experimentation" phase of the learning cycle, thereby accelerating the transition from novice to competent practitioner.

4. Methodology

4.1 Research Design

A quasi-experimental, mixed-methods research design was employed. The study utilized a pre-test/post-test control group architecture to measure empirical performance differences, supplemented by post-intervention surveys and semi-structured interviews to gather qualitative data on user experience.

4.2 Participants

The study cohort comprised 120 second-year automotive engineering students from a technical vocational institute. Participants were randomly assigned to two groups:

Control Group ($n = 60$): Utilized traditional OEM (Original Equipment Manufacturer) printed service manuals and tablet-based 2D PDFs.

Experimental Group ($n = 60$): Utilized a wearable AR headset (Microsoft HoloLens 2) running a custom-developed Unity3D training application.

Prior to the experiment, a baseline knowledge test confirmed there was no statistically significant difference in prior mechanical aptitude between the two groups ($p > 0.05$).

4.3 The AR Intervention Design

The AR application was designed specifically for this study, focusing on the diagnosis and replacement of a timing belt on a standardized internal combustion engine—a task known for its high procedural complexity and strict tolerance requirements.

The AR system provided:

3D Holographic Overlays: Color-coded digital highlights superimposed directly over physical bolts, tensioners, and pulleys.

Step-by-Step Animations: Animated visual sequences showing the exact rotational force and direction required for component removal.

Hands-free Navigation: Voice commands and gesture recognition allowing students to progress through steps without putting down their tools.

4.4 Instruments and Metrics

Task Completion Time (TCT): Measured in minutes from the initiation of the task to successful completion.

Procedural Error Rate (PER): Measured by observing the number of critical and non-critical errors committed during the task (e.g., applying incorrect torque, missing a sequence step).

NASA Task Load Index (NASA-TLX): A multidimensional scale used to assess perceived cognitive workload across six subscales (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration).

System Usability Scale (SUS): A 10-item questionnaire measuring the subjective usability of the AR system.

4.5 Data Analysis

Quantitative data were analyzed using SPSS v28. Independent samples t-tests were conducted to compare the means of the control and experimental groups. The significance level was set at $\alpha = 0.05$. The t-statistic was calculated using the standard formula:

$$t = (\bar{x}_1 - \bar{x}_2) / \sqrt{(s_1^2/n_1 + s_2^2/n_2)}$$

5. Results

5.1 Practical Skill Performance: Time and Accuracy

The experimental (AR) group significantly outperformed the control group in practical workshop metrics.

Table 1: Comparison of Task Completion Time and Procedural Errors

Metric	Group	Mean (M)	Std. Dev (SD)	t-value	p-value
Task Completion Time (mins)	Control	48.5	6.2	8.42	< 0.001
	AR Experimental	36.8	4.1		
Procedural Errors (Count)	Control	4.2	1.5	7.95	< 0.001
	AR Experimental	1.8	0.8		

As detailed in Table 1, the AR group completed the complex repair task an average of 11.7 minutes faster than the control group. Furthermore, the procedural error rate was reduced by more than half ($M = 1.8$ vs $M = 4.2$). Both results were statistically significant ($p < 0.001$), indicating a strong efficacy of the AR intervention in facilitating rapid, accurate skill execution.

5.2 Cognitive Load Assessment (NASA-TLX)

Post-task cognitive load was measured out of a maximum score of 100 (where lower scores indicate lower cognitive burden).

Table 2: NASA-TLX Cognitive Load Scores

Subscale	Control Group (M)	AR Group (M)	Mean Difference
Mental Demand	72.4	51.2	-21.2
Physical Demand	45.6	48.1	+2.5
Temporal Demand	68.3	55.4	-12.9
Effort	70.1	54.3	-15.8
Frustration	58.7	32.5	-26.2

The AR group reported a drastically lower Mental Demand and Frustration level compared to the control group. This supports the Cognitive Load Theory hypothesis: by overlaying instructions directly onto the workspace, the AR system eliminated the need for users to constantly mentally map 2D diagrams to 3D reality. Interestingly, Physical Demand was slightly higher for the AR group, likely due to the weight of the HoloLens 2 headset (approximately 566 grams) worn during the 36-minute physical task.

5.3 Usability and Learner Perception

The experimental group completed the System Usability Scale (SUS) regarding the AR hardware and software. The system achieved a mean SUS score of 82.5 (SD = 8.1), which falls into the "Excellent" category.

Qualitative interviews revealed overwhelming enthusiasm. One participant noted: "Seeing the exact bolt light up in my field of vision meant I didn't second-guess myself. I didn't have to walk back to the workbench to check the manual." However, minor themes of fatigue emerged, with 15% of participants noting neck strain or mild visual discomfort after prolonged continuous use.

6. Discussion

The findings of this study provide robust empirical support for the integration of Augmented Reality in vocational automotive training, resonating strongly with the technological innovation themes of ICCMETS 2026.

6.1 Enhancing Procedural Efficacy

The significant reduction in Task Completion Time and Procedural Errors demonstrates that AR acts as a powerful scaffolding tool. In traditional settings, a novice technician must look at a manual, hold the visual information in their working memory, locate the corresponding physical part, and execute the action. AR collapses these steps into a single, seamless cognitive action (Muslim, 2026). The spatial presence of 3D holograms ensures that tolerances and torque angles are visually represented in real-time, greatly minimizing catastrophic errors during repair.

6.2 Managing Cognitive Load in Complex Systems

The NASA-TLX data revealed a massive 26.2-point drop in learner frustration. In vocational education, high frustration and cognitive overload are primary drivers of student disengagement. By converting abstract, highly technical data into intuitive visual overlays, AR democratizes complex engineering concepts, making them accessible to a broader range of learning styles (Ndiwu & Athumani, 2026).

6.3 Limitations and Implementation Challenges

While the efficacy is clear, practical implementation in TVET institutions faces hurdles. The initial capital expenditure for enterprise-grade AR hardware (e.g., HoloLens 2, Magic Leap) and the specialized software development required to map complex engine bays remain high (Liu, Zhan, & Zhao, 2023). Furthermore, the slight increase in physical demand suggests that while AR is excellent for focused, module-based training, it may not yet be ergonomically suitable for full 8-hour shift deployments in actual repair shops.

6.4 Implications for Vocational Institutions

For TVET policymakers and curriculum designers, the mandate is clear: AR should transition from a novelty to a core pedagogical utility. Institutions should adopt a hybrid deployment paradigm, utilizing traditional instruction for baseline theory, but deploying AR specifically for high-complexity, high-risk procedural tasks (e.g., EV high-voltage battery maintenance).

7. Conclusion and Future Work

As the automotive sector hurtles toward an era of electrification and autonomous mobility, vocational training frameworks must evolve concurrently. This study unequivocally demonstrates that Augmented Reality significantly enhances the efficacy of automotive repair training by reducing procedural errors, accelerating task completion, and lowering extraneous cognitive load. AR effectively bridges the persistent divide between classroom theory and workshop reality, providing a scalable, immersive learning environment.

Future research should focus on longitudinal studies to determine the long-term retention of skills acquired via AR without the headset present. Additionally, integrating Artificial Intelligence (AI) with AR to create adaptive, real-time diagnostic guidance systems represents the next frontier in educational technology—a topic ripe for exploration in subsequent ICCMETS conferences.

References

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