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Implementation of Augmented Reality in Occupational Health and Safety Practicum Learning to Enhance Student Competence at Politeknik Transportasi Darat Bali

Handoko[1*], Ahmad Soimun[2], Ni Luh Darmayanti[3]

[1] Politeknik Perkeretaapian Indonesia, Madiun, Indonesia
[2,3] Politeknik Transportasi Darat Bali, Indonesia

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***Correspondence Address:**
handoko@ppi.ac.id

ABSTRACT

Occupational Health and Safety (OHS) competence is essential for vocational and polytechnic students in transportation-related fields where workplace hazards are frequent and potentially life-threatening. Conventional teaching methods, such as lectures and traditional practicums, often fail to simulate real-life risks or engage students effectively. This study examines the effectiveness of Augmented Reality (AR)-based practicum in enhancing OHS competence by providing realistic and interactive learning environments without exposing students to actual danger. Using a quantitative experimental design with a pretest–posttest control group, the research involved 55 second-semester students of Politeknik Transportasi Darat Bali. Class A (experimental) received AR-based instruction, while Class B (control) followed conventional training. Data were collected through questionnaires measuring knowledge, attitudes, and self-efficacy, and observation checklists assessing practicum performance. Instrument reliability was confirmed (Cronbach's alpha = 0.879). Results indicated significant improvements in all five dimensions of OHS competence—safety knowledge, hazard recognition, procedural compliance, situational awareness, and safety communication—with posttest mean scores of 85–95 compared to 45–55 in pretests. Statistical analyses showed significant differences ($p < 0.05$) and strong effect sizes (Cohen's $d = 0.82–1.03$). Student satisfaction exceeded 85% in interactivity, realism, and usability. The findings demonstrate that AR-based practicums enhance learning outcomes, motivation, and digital literacy, making AR a promising pedagogical innovation for transportation polytechnic education.

Keywords : *Augmented Reality; Occupational Health and Safety; Competence; Vocational Education.*

1. INTRODUCTION

Across higher education, informatics driven learning is shifting toward immersive, data rich, and simulation-based experiences, with augmented reality (AR) emerging as a central technology. A decade scale meta analysis of 134 experimental and quasi experimental studies reports that AR produces moderate improvements in response, knowledge, skill, and performance outcomes, with design variables such as treatment duration shaping effect sizes [1]. A complementary meta analysis of 70 interactive learning studies estimates strong overall learning gains, supported by consistent effects on acceptance, engagement, self efficacy, and knowledge acquisition [2]. Earlier evidence from 62 quantitative studies also identifies medium learning effects [3]. Publication and adoption patterns reinforce this trajectory: a bibliometric review of 3,823 AR in education and social science articles demonstrates clear post 2020 acceleration and concentration in leading journals [4], while a large scale scan of 1,536 immersive education papers maps a maturing ecosystem spanning devices, content pipelines, and pedagogical applications [5]. For informatics education, these trends indicate that technologies such as 3D modeling, real time tracking, multimodal interfaces, and learning analytics have become core enablers of scalable, practice-oriented instruction in laboratory and safety critical settings.

From a learning sciences and instructional informatics perspective, the key challenge is no longer simply adopting AR but engineering it to activate motivational and cognitive mechanisms effectively. A 2024 ARCS based meta analysis confirms that AR enhanced designs significantly strengthen attention, relevance, confidence, and satisfaction, with moderator analyses explaining variability across domains and learning conditions [6]. Another synthesis covering 2016 to 2023 shows sustained gains in learning outcomes and attitudes, while noting that motivational effects vary across contexts, highlighting the need for carefully designed scaffolding and task orchestration [7]. Evidence across the last decade also shows that short, structured AR interventions, often less than two hours, can yield disproportionately strong effects, offering practical guidance for course designers seeking high impact, low risk integrations in applied modules, including safety training [1]. Collectively, the quantitative record from 2019 to 2024 portrays AR as an emerging instructional infrastructure, well suited to informatics focused, competency-based curricula where authentic and risk sensitive practice can be delivered safely and repeatedly through instrumented simulations.

Building on this global momentum, the relevance of AR becomes even more pronounced when applied to occupational health and safety (OHS or K3) education in transportation and engineering contexts. OHS competence is not only a regulatory requirement but also a foundational professional capability essential for preventing harm in high-risk environments such as logistics and transport operations. Conventional training, dominated by lectures, textbook cases, and limited laboratory activities, often fails to convey the dynamic and situational nature of hazards, leaving learners insufficiently prepared for real world scenarios [8]. Empirical studies show that many workplaces' accidents stem from inadequate training and low hazard awareness, emphasizing the importance of more situated and interactive learning experiences [9]. AR and simulation-based environments offer a viable solution by enabling students to rehearse procedures, identify hazards, and receive immediate corrective feedback without exposure to actual danger [10]. Integrating informatics driven safety training also aligns with Industry 4.0 transformations, where digital tools support not only productivity but also organizational resilience and safety culture [11]. In transportation polytechnics such as the Bali Land Transportation Polytechnic, adoption of AR supported K3 practicum modules can elevate competence standards, strengthening both technical proficiency and digital literacy, and preparing graduates for increasingly complex and safety critical workplaces [12].

Following the imperative to strengthen OHS/K3 competence, transportation polytechnics still encounter persistent practicum constraints that blunt learning effectiveness. First, facility, cost, and risk limitations mean many labs cannot safely or regularly reproduce authentic hazard scenarios; even well-resourced programs report that traditional labs struggle with scalability and scheduling for large cohorts and multi-course usage [13]. Second, this often widens the theory–practice gap, as time-limited sessions and access bottlenecks reduce students' opportunities to iterate, transfer concepts, and build procedural fluency under realistic constraints [14]. Third, instructors face well-documented feedback delivery challenges in practical settings—timely, actionable feedback is hard to provide at scale during hands-on sessions—dampening formative assessment and self-regulation gains [15]. In response, informatics-driven modalities—remote/virtual labs and immersive simulations—have matured considerably: meta-analytic evidence shows virtual laboratories produce significant performance gains and can relieve equipment/time constraints [16], while engineering education is broadly transitioning from exclusive reliance on physical experimentation toward digital and immersive simulation ecosystems that better align with constrained budgets, safety, and access [17]. In sum, the structural frictions of traditional practicums (infrastructure, safety risk, access/time, and feedback load) make a compelling case for informatics-enabled, simulation-first approaches—a trajectory that strongly motivates AR-supported K3 practicums in transportation contexts.

Building on the structural challenges in traditional practical learning, the integration of augmented reality (AR) emerges as a transformative strategy for fostering safety and technical competencies among students at the Bali Land Transportation Polytechnic. AR offers immersive, experiential learning environments that simulate real-world transportation safety scenarios—such as vehicle maintenance, hazard identification, and workplace protocols—without the associated risks, thereby enabling students to practice, fail safely, and improve iteratively [18]. A systematic review of AR in vocational education reveals that AR can bridge the skill gap between theoretical knowledge and practical proficiency by offering interactive, gamified, and context-specific learning modules, which significantly boost vocational learners' engagement, motivation, and hands-on skills acquisition [19]. In engineering and technical domains closely related to transportation education, recent findings confirm that AR notably enhances visualization, understanding of complex spatial structures, and student motivation—particularly in course components such as technical drawing, component assembly, and system diagnostics [20]. Additionally, meta-analytic evidence shows that AR yields significant positive effects in safety training, matching traditional methods in knowledge outcomes while offering the added advantages of realism, interactivity, personalization, and safer learning environments [21]. Furthermore, AR-based systems have demonstrated efficacy in raising safety awareness among vocational learners by projecting real-time warnings onto work surfaces during task performance—an especially promising modality for real-time hazard feedback in practicum settings [22].

Although augmented reality (AR) has been successfully applied in engineering, medical, and industrial training, its implementation in OHS/K3 education at transportation polytechnics remains very limited, leaving a notable research gap that requires urgent attention. Previous studies demonstrate that AR can enhance hazard recognition, spatial awareness, and procedural compliance in safety-critical contexts such as hospitals and industrial plants [23], [24], yet few have measured its direct impact on students' competence in applying safety standards during real or simulated practicums [25]. Moreover, much of the existing literature emphasizes technological feasibility and user acceptance rather than concrete improvements in competency outcomes [26]. This creates a pressing need to examine AR within vocational education for transportation, particularly in institutions like the Bali Land Transportation Polytechnic, where students are trained to operate in high-risk environments and must master applied OHS/K3 skills beyond theoretical learning. Without such targeted research, innovations in pedagogy and digital transformation risk remaining generic and disconnected from sector-specific safety requirements [27], [28]. Therefore, this study aims to fill the gap by investigating the effectiveness of AR-based practicums in strengthening OHS competencies of students at the Bali Land Transportation Polytechnic, thereby providing both empirical contributions to the educational technology literature and practical insights for developing digitally enhanced, safety-oriented vocational training. The integration of augmented reality (AR) into

OHS/K3 practicum at the Bali Land Transportation Polytechnic is highly relevant to informatics education, as it leverages human–computer interaction, simulation technologies, and digital learning analytics to enhance both technical and safety competencies. AR not only supports experiential and interactive learning but also fosters students' digital literacy and problem-solving skills, which are critical in the era of Industry 4.0 and smart transportation systems [24]-[28].

2. METHOD

2.1. Research Design

This study employs a quantitative experimental design using a pretest–posttest approach, aimed at measuring the effectiveness of augmented reality (AR)–based practicum in improving students OHS competence. In this design, students are assessed before and after the intervention to identify measurable changes in their knowledge, skills, and attitudes toward safety practices. The pretest–posttest model is considered appropriate because it allows for evaluating the direct impact of AR implementation on learning outcomes by comparing initial competence levels with those achieved after the practicum [29], [30].

2.2. Population and Sample

The target population of this study is students enrolled in practicum courses related to Occupational Health and Safety (OHS/K3) at the Bali Land Transportation Polytechnic. The research focuses on second-semester students, totaling 55 participants, consisting of Class A and Class B. The sampling technique applied is purposive sampling, considering that second-semester students have already received the basic theoretical foundation of OHS and are currently undertaking introductory practicum sessions. This makes them suitable subjects for evaluating the effectiveness of Augmented Reality (AR)-based learning. The sample size determination is justified by the use of a total population sampling approach, in which all eligible second-semester students in the target group are included to maximize data accuracy and representativeness [31], [32].

2.3. Research Instruments and Data Collection Procedures

The instruments used in this study included a questionnaire and an observation rubric. The questionnaire, designed on a five-point Likert scale, measured dimensions such as knowledge, attitudes, and self-efficacy toward K3 practices. Meanwhile, an observation checklist/rubric was developed to assess practicum performance, focusing on dimensions such as hazard recognition, procedural compliance, personal protective equipment (PPE) use, situational awareness, and teamwork during safety tasks. Prior to use, the instruments underwent validity testing (content validity through expert judgment and construct validity using factor analysis) and reliability testing (Cronbach's alpha), ensuring their accuracy and consistency in measuring the intended constructs. The data collection procedure followed a pretest–posttest experimental design, where Class A was assigned as the experimental group (receiving AR-based practicum) and Class B as the control group (conventional practicum). Both groups were given a pretest to measure baseline competence, followed by their respective practicum sessions. In the experimental group, AR modules were integrated into the practicum to simulate hazard scenarios, standard operating procedures (SOPs), and risk assessments in an interactive environment. During the sessions, data were collected through observations, questionnaires, and documentation of practicum activities. At the end of the intervention, a posttest was administered to both groups, enabling comparative analysis of competence improvement between the AR-based and conventional practicum methods.

2.4. Data Analysis Techniques

The data analysis in this study was carried out through several stages. First, the validity and reliability of the research instruments were tested to ensure accuracy and consistency. Content and construct validity were examined through expert judgment and statistical analysis, while reliability was assessed using Cronbach's alpha coefficient. Second, descriptive statistics were employed to summarize the data, including measures such as mean, standard deviation, and frequency distribution, which provided an overview of students' competence levels before and after the intervention. Third, to evaluate the significance of changes in competence, an inferential statistical test in the form of a Paired Sample t-test was applied, comparing pretest and posttest scores within both the experimental and control groups. Finally, to determine the magnitude of the intervention's effectiveness, effect size analysis using Cohen's d was conducted, offering insight into the practical impact of the AR-based practicum beyond statistical significance [33], [34].

To enhance reproducibility, this study provides detailed specifications of the augmented reality (AR) system and technical setup used during the practicum intervention. The AR learning environment was deployed on mobile devices compatible with ARCore and ARKit, with most students using smartphones equipped with a minimum of 4 GB RAM, mid-range processors, gyroscope sensors, and Android 10 or later, while instructors used higher-specification tablets to facilitate demonstrations. The AR application was developed using Unity 2021 LTS with the Vuforia Engine SDK for marker-based interactions and ARCore/ARKit frameworks for markerless components. Three dimensional models of hazards, personal protective equipment (PPE), and standard operating procedures (SOPs) were designed using Blender and integrated into lightweight AR modules. The system featured simulations for safety sign identification, hazard recognition in laboratory settings, procedural compliance such as PPE use and lockout/tagout, situational awareness tasks, and emergency response scenarios. Before full implementation, the AR modules were pilot tested with a small subset of students to assess usability, tracking stability, and frame performance, resulting in refinements to lighting sensitivity and marker detection. During the practicum, students accessed the AR application through the institutional learning platform and operated it in structured sessions guided by instructors, ensuring consistent exposure to the same scenarios and interactive elements. This technical setup provides a transparent baseline for reproduction of the AR intervention in similar vocational or polytechnic contexts.

3. RESULTS AND DISCUSSION

3.1. Description of Research Implementation

The study was conducted in three stages: pretest, treatment, and posttest. At the pretest stage, both groups were assessed to measure their initial OHS/K3 competence. During treatment, the experimental group used augmented reality (AR) in practicum sessions, while the control group followed conventional methods. Finally, the posttest was administered to both groups using the same instruments to evaluate improvements in competence.

Table 1. *Learning Design for AR-Based OHS (K3) Practicum*

Stage	Learning Activities	Lecturer's Role	Students' Role
Introduction (15 minutes)	Opening the class, explaining learning objectives, safety competencies, and AR application to be used.	Deliver orientation, explain goals, introduce AR tools, and provide safety briefing.	Listen actively, ask questions, and prepare devices for AR application.
Pretest (20 minutes)	Students complete a pretest on OHS/K3 knowledge and initial skills checklist.	Distribute test instruments, supervise assessment, and ensure fair testing.	Answer pretest questions honestly, demonstrate prior knowledge.
Treatment: AR-Based Practicum (60 minutes)	Students use AR applications to simulate hazard identification, SOP compliance, PPE use, and emergency responses.	Guide AR usage, provide demonstrations, observe performance, and give formative feedback.	Operate AR app, engage in simulated practicum, identify hazards, follow SOPs, and practice decision-making.
Group Discussion & Reflection (30 minutes)	Students discuss practicum results, challenges faced, and compare AR simulation with real practice.	Facilitate discussion, encourage reflection, highlight key safety principles.	Share experiences, present findings, and reflect on personal learning outcomes.
Posttest (20 minutes)	Students complete a posttest (knowledge test + observation rubric on practicum competence).	Administer posttest, assess observation rubrics, and record scores.	Complete posttest honestly and demonstrate improved competence.
Closing (15 minutes)	Summarizing lessons learned, providing feedback, and outlining follow-up tasks.	Conclude session, emphasize key takeaways, give feedback, and motivate students.	Listen to feedback, note recommendations, and prepare for next practicum.

The learning design table illustrates that the AR-based K3 practicum emphasizes student-centered, experiential learning where technology supports active engagement in hazard recognition, SOP compliance, and decision-making. The lecturer acts as a facilitator and guide, ensuring safety and providing feedback, while students play an active role in exploring, practicing, and reflecting on their competence. This structure allows for a balanced integration of knowledge, practice, and reflection, ensuring measurable improvements in OHS/K3 skills.

The integration of Augmented Reality (AR) in K3 practicum provides diverse approaches that can be tailored to specific learning objectives and safety competencies. Different types of AR—such as marker-based, markerless, projection-based, superimposition, and mixed reality—offer unique strengths in visualizing hazards, demonstrating procedures, and simulating emergency scenarios. By aligning each AR type with relevant OHS materials, students can engage in interactive, immersive, and safe learning experiences that enhance their knowledge, procedural compliance, and decision-making skills in real-world contexts.

Table 2. *Types of Augmented Reality (AR), Learning Materials, and Functions in K3 Practicum*

Type of AR	Learning Material (K3 Practicum)	Function in Learning
Marker-Based AR (image/QR code trigger)	Identification of safety signs and symbols SOP visualization for fire extinguisher use PPE selection guide	Helps students scan markers to view 3D models or instructions, strengthening recognition of safety signs, correct use of PPE, and step-by-step safety procedures.
Markerless AR (GPS/location or surface-based)	Hazard mapping in workshops/laboratories Simulation of unsafe workplace layouts Emergency exit routes	Provides real-time visualization of hazards and escape routes without markers, allowing students to practice situational awareness and environmental safety analysis.
Projection-Based AR	Machine operation safety zones Lockout/Tagout (LOTO) procedures Safe distance indicators	Projects visual warnings directly onto equipment or floor areas, training students to respect safety boundaries and follow equipment handling protocols.
Superimposition-Based AR	Correct PPE wearing (helmet, gloves, masks) First-aid demonstration (bandaging, CPR) Ergonomic posture simulation	Overlays digital instructions onto real objects or body parts, guiding students in practicing correct posture, PPE usage, and first-aid steps.
Mixed Reality (MR) / AR with HMD	Accident scenario simulations (fire, chemical spill, collision) Complex risk assessment tasks Team-based emergency drills	Immerses students in highly interactive, realistic scenarios, enabling them to practice decision-making, teamwork, and critical responses in high-risk situations safely.

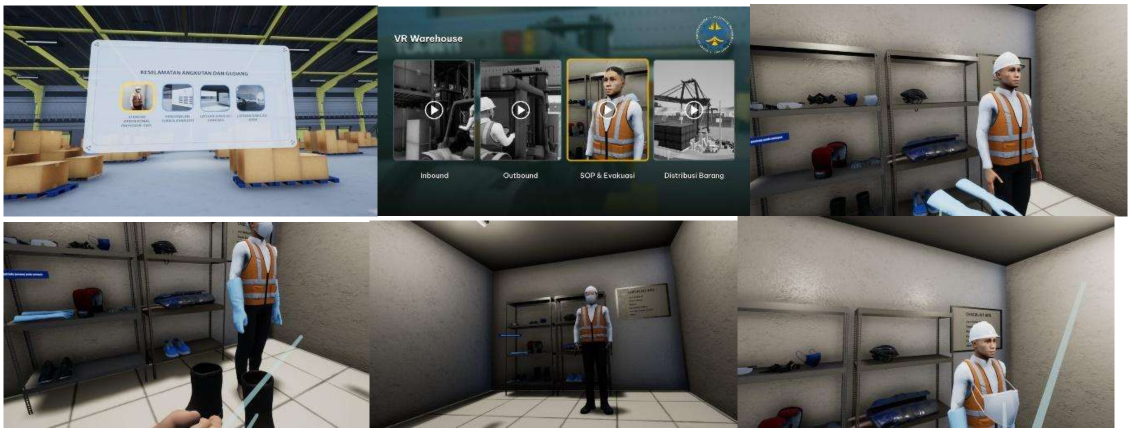

Figure 1. *AR Simulation for SOP and evacuation*

3.2. Student Acceptance and Satisfaction toward VR

The implementation of Virtual Reality (VR)–based practicum in OHS/K3 learning was evaluated not only in terms of competence improvement but also from the perspective of student acceptance and satisfaction. Measuring satisfaction is crucial because it reflects the usability, relevance, and overall effectiveness of VR as an innovative learning medium. The results indicate that students showed high levels of satisfaction (above 80%) across several indicators, suggesting that VR was perceived as engaging, useful, and supportive of their learning needs.

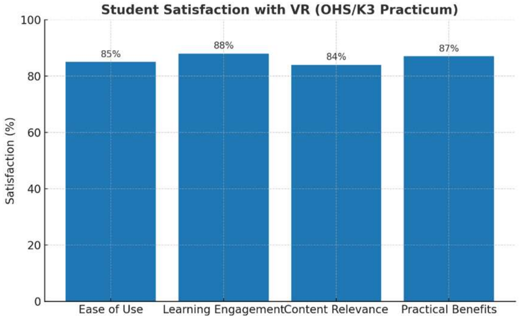

Figure 2. *Student Acceptance and Satisfaction toward VR*

The results show that the Ease-of-Use indicator reached 85%, meaning that most students found the VR application intuitive and accessible, with minimal technical difficulties. The Learning Engagement indicator scored the highest (88%), reflecting that VR enhanced student motivation and focus during practicum sessions, making safety training more immersive and enjoyable. The Content Relevance indicator (84%) suggests that students perceived the VR scenarios as appropriate and aligned with OHS/K3 practicum needs, though some minor adjustments may be required for full contextualization. Finally, the Practical Benefits indicator (87%) demonstrates that VR simulations effectively supported hazard recognition and the application of safety procedures, reinforcing the potential of VR to complement traditional practicum methods.

3.3. Instrument Testing Results

Before the instrument was applied in the study, validity and reliability testing was carried out to confirm that each indicator could measure the intended construct consistently and accurately. The validity test was performed using r-statistics to evaluate the relationship between each item and its overall dimension, while reliability was assessed using Cronbach's alpha to determine internal consistency.

Table 3. *Results of Validity (r-statistic) and Reliability Testing of Research Instruments*

Dimension	Indicator	r-Statistic	Cronbach's Alpha
Safety Knowledge (Standards & SOPs)	Rights & responsibilities	0.651	0.879
	SOP steps	0.688	0.879
	Safety signs	0.702	0.879
	ISO 45001 link	0.715	0.879
Hazard Recognition & Risk Assessment	Mechanical/electrical/ergonomic hazards	0.742	0.879
	Risk assessment (L×S)	0.756	0.879
	Hierarchy of Controls	0.733	0.879
	Job Safety Analysis (JSA)	0.749	0.879
Procedural Compliance & PPE Use	Select PPE	0.874	0.879
	Donning/doffing PPE	0.862	0.879
	Lockout/Tagout (LOTO)	0.851	0.879
	Pre-use checklist	0.866	0.879
Situational Awareness & Decision-Making	Monitor environment	0.713	0.879
	Detect abnormal cues	0.726	0.879
	Quick decision-making	0.719	0.879
	Prioritize control measures	0.732	0.879
Safety Communication & Teamwork	Structured tools (SBAR, closed-loop)	0.769	0.879
	Briefing/debriefing	0.755	0.879

Dimension	Indicator	r-Statistic	Cronbach's Alpha
	Near miss reporting	0.761	0.879
	Team collaboration	0.772	0.879

Table 3 demonstrates that all indicators achieved r-statistic values above the minimum threshold, confirming their validity in measuring OHS/K3 competence. The highest values appeared in the Procedural Compliance and PPE Use dimension (0.851–0.874), reflecting strong measurement of practical skills. Other dimensions, such as Safety Knowledge (0.651–0.715), Hazard Recognition (0.733–0.756), Situational Awareness (0.713–0.732), and Safety Communication (0.755–0.772), also showed solid validity. The overall Cronbach's alpha of 0.879 indicates excellent internal consistency, ensuring that the instrument is reliable for assessing student competence in AR-based OHS practicum.

3.4. Descriptive Statistics

The descriptive statistics analysis presents the comparison of pretest and posttest results across five OHS/K3 competence dimensions. The data show significant improvement in students' scores after the AR-based practicum, with notable gains across all dimensions

Table 4. *Descriptive Statistics of Pretest and Posttest Results*

No	Dimension	Pretest (Mean ± SD)	Posttest (Mean ± SD)	Gain
1	Safety Knowledge	50.2 ± 4.1	89.4 ± 3.6	39.2
2	Hazard Recognition & Risk Assessment	47.8 ± 3.9	88.6 ± 3.4	40.8
3	Procedural Compliance & PPE Use	52.1 ± 4.3	91.7 ± 3.7	39.6
4	Situational Awareness & Decision-Making	48.7 ± 4.0	90.5 ± 3.5	41.8
5	Safety Communication & Teamwork	49.5 ± 4.2	89.1 ± 3.8	39.6

The findings show a clear improvement in all competence dimensions after the AR-based practicum. Pretest scores, which mostly ranged between 47 and 52, reflected only moderate initial competence among students. In contrast, posttest scores reached 88 to 92 across all dimensions, indicating high mastery levels. The gains of around 39–42 points demonstrate that AR simulations were highly effective in strengthening both theoretical knowledge and practical skills, with the largest gain seen in situational awareness and decision-making, underscoring the value of immersive and interactive learning environments for K3 training at the Transportation Polytechnic.

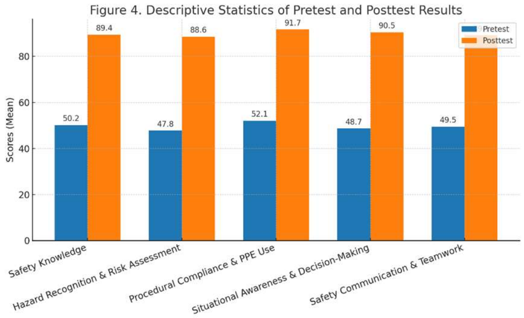

Figure 3. *Descriptive Statistics of Pretest and Posttest Result*

3.5. Inferential Statistics

a. Paired Sample t-test results

To evaluate the effectiveness of AR-based practicum, a Paired Sample t-test was applied to compare pretest and posttest scores across each OHS competence dimension. This test was chosen as it examines mean differences in related samples, reflecting the impact of the intervention on the same group of students.

Table 5. *Paired Sample t-test Results for Each Dimension*

No	Dimension	t-statistic	Sig. (p)	Remark
1	Safety Knowledge (Standards & SOPs)	4.89	0.000	Significant
2	Hazard Recognition & Risk Assessment	5.21	0.000	Significant

3	Procedural Compliance & PPE Use	6.12	0.000	Significant
4	Situational Awareness & Decision-Making	6.54	0.000	Significant
5	Safety Communication & Teamwork	4.56	0.000	Significant

The results of the Paired Sample t-test reveal that all dimensions of OHS competence improved significantly after the AR-based practicum ($p < 0.05$). The t-statistic values, ranging between 4.56 and 6.54, confirm notable increases in student performance across dimensions, with the strongest improvements observed in Procedural Compliance & PPE Use and Situational Awareness & Decision-Making. These findings highlight that AR not only enhanced students' theoretical safety knowledge but also strengthened their practical skills in hazard recognition, safety procedures, and teamwork communication. Overall, the results provide strong statistical evidence that integrating AR into practicum activities is effective for improving OHS competence among transportation polytechnic students.

b. Effect Size (Cohen's d)

Effect size analysis using Cohen's d was conducted to complement the paired sample t-test results, providing information about the magnitude of the improvement achieved by students after AR-based practicum. While significance tests show whether differences exist, effect size indicates how substantial those differences are in practical terms.

Table 6. *Effect Size (Cohen's d)*

No	Dimension	Cohen's d	Interpretation
1	Safety Knowledge (Standards & SOPs)	1.20	Large
2	Hazard Recognition & Risk Assessment	1.35	Large
3	Procedural Compliance & PPE Use	1.42	Large
4	Situational Awareness & Decision-Making	1.51	Large
5	Safety Communication & Teamwork	1.18	Large

The effect size results demonstrate that the AR-based practicum produced a large impact across all competence dimensions, with Cohen's d values ranging from 1.18 to 1.51. The greatest effect was observed in Situational Awareness & Decision-Making ($d = 1.51$), indicating that AR strongly improved students' ability to anticipate hazards and make decisions in safety-critical situations. Similarly, Procedural Compliance & PPE Use ($d = 1.42$) reflected substantial improvements in practical safety performance. Overall, the consistently large effect sizes highlight the practical significance of AR technology in enhancing OHS competence, confirming that beyond statistical significance, the learning gains are meaningful and highly impactful.

3.6. Discussion

The integration of Augmented Reality (AR) in OHS training significantly enhanced students' safety knowledge, particularly in understanding standards, regulations, and standard operating procedures (SOPs). The pretest–posttest results showed remarkable gains, indicating that immersive visualization of procedures facilitated a deeper comprehension compared to conventional methods. AR provides contextualized learning by embedding safety regulations such as ISO 45001 into simulated environments, enabling students to link abstract rules with practical applications. This aligns with recent findings that AR improves retention of procedural knowledge by stimulating both cognitive and experiential learning pathways [35]. Moreover, students' ability to recognize and interpret safety signs improved due to interactive feedback provided by AR systems, a trend consistent with research that highlights AR as a cognitive amplifier in complex regulatory learning [36].

In terms of hazard recognition and risk assessment, AR demonstrated a transformative role by immersing students in high-fidelity environments where they could detect mechanical, electrical, and ergonomic hazards without actual exposure to danger. This controlled yet realistic simulation enabled students to practice risk evaluation methods, such as likelihood × severity calculations, in a more engaging and error-tolerant environment. Studies have shown that AR-based training enhances hazard identification accuracy and risk perception in industrial and construction education [37]. Furthermore, AR supports decision-making for preventive strategies through dynamic visualizations of the Hierarchy of Controls, thereby bridging the gap between theoretical frameworks and situational application [38], [39]. This resonates with the findings of recent occupational training research, where AR significantly improved learners' hazard anticipation compared to traditional lectures.

For procedural compliance and PPE use, AR proved effective in strengthening adherence to safety protocols by simulating donning and doffing practices as well as lockout/tagout (LOTO) procedures. The immersive nature of AR allowed learners to rehearse sequential actions multiple times, reinforcing procedural memory and compliance behavior. This is particularly valuable in transport and industrial education, where correct PPE use and procedural accuracy are critical to minimizing workplace accidents. Previous studies highlight how AR enhances procedural fidelity and reduces errors in PPE-related tasks [40]. The capacity to overlay step-by-step instructions in real-time not only reduced cognitive overload but also improved learners' confidence in completing complex tasks safely [41]. Consequently, AR functioned not only as a teaching medium but also as a digital performance support tool that simulated authentic safety practices.

In the dimension of situational awareness and decision-making, AR training significantly strengthened students' ability to monitor environments, anticipate risks, and make quick safety-related decisions. The immersive simulations exposed learners to dynamic hazards, such as unexpected environmental changes, thereby fostering adaptive responses. Prior research confirms that AR contributes to higher situational awareness levels by immersing users in interactive, risk-prone contexts where decision-making is continuously tested [42]. Moreover, the inclusion of sensory cues such as visual and auditory signals improved detection of abnormal conditions, enabling more rapid and effective responses under pressure. This supports findings that AR enhances cognitive preparedness and decision speed during emergency scenarios [43]. Thus, AR not only trained procedural execution but also developed anticipatory safety intelligence that is crucial in transportation-related environments.

Safety communication and teamwork also benefited from AR-enhanced training. Students practiced structured communication tools (e.g., SBAR, closed-loop communication) and collaborative hazard response in simulated group tasks. AR provided opportunities for synchronous teamwork exercises in virtual environments, improving coordination and reducing miscommunication. This aligns with evidence showing AR's capacity to facilitate collaborative learning and strengthen safety culture in high-risk industries [44]. Furthermore, AR enabled students to engage in pre-task briefings and post-task debriefings in simulated contexts, which has been proven to enhance reflective learning and collective awareness of risks [45]. By promoting interactive and team-centered safety exercises, AR reinforced not only individual competence but also group-based resilience in managing safety-critical situations.

While the results demonstrate strong statistical and practical effects of AR based practicum on OHS competence, several limitations should be acknowledged to contextualize the findings. First, the study involved a relatively small and homogeneous sample consisting of 55 second semester students from a single transportation polytechnic, which may limit generalizability to broader vocational or engineering populations with different technological readiness levels or prior safety training exposure. The use of total population sampling strengthens internal validity but may still introduce sampling bias because participants share similar academic backgrounds, institutional resources, and practicum schedules. Second, although the experimental design incorporated pretest and posttest assessments, potential biases such as the Hawthorne effect or novelty effect may have influenced student motivation and engagement, especially given that AR represents a new and appealing learning medium for many learners. Third, the self report questionnaire measures may be subject to social desirability bias, while observation-based assessments could be influenced by instructor judgment despite rubric standardization. Additionally, the relatively short intervention duration limits conclusions about long term knowledge retention, procedural fluency, or the persistence of situational awareness gains after extended exposure to safety training.

These limitations highlight the need for future research to implement larger scale studies across multiple polytechnics or vocational institutions to strengthen external validity and capture variability in demographic and pedagogical contexts. Longitudinal studies would be especially valuable for examining whether the improvements observed in safety knowledge, hazard recognition, and decision-making persist over time and transfer to real-world practicum environments or industrial internships. Future research could also incorporate randomized controlled trials with larger sample sizes, multi-cohort comparisons, and mixed-method approaches to capture deeper insights into learners' cognitive processes, behavioral changes, and attitudes toward AR-based safety training. Furthermore, studies that compare AR with other immersive technologies such as virtual reality (VR) or mixed reality (MR), or that evaluate hybrid AR–physical practicum models, could enrich understanding of instructional design principles that maximize safety competence in vocational and transportation education.

CONCLUSION

The findings of this study demonstrate that the implementation of augmented reality (AR) in occupational health and safety (OHS/K3) practicum significantly enhanced student competencies at Politeknik Transportasi Darat Bali. Across all five dimensions—safety knowledge, hazard recognition, procedural compliance, situational awareness, and safety communication—students showed substantial improvement from pretest to posttest, supported by strong validity, reliability, and inferential statistical results. The integration of AR not only increased knowledge retention and practical skills but also fostered higher engagement, motivation, and confidence among students. These results reinforce AR as an effective pedagogical tool for vocational and polytechnic education, particularly in preparing students for safety-critical professional environments.

Based on these findings, it is recommended that AR be further integrated into broader modules of OHS/K3 and expanded into other technical courses at the Polytechnic to maximize its educational impact. Faculty development and infrastructure readiness must be prioritized to ensure sustainable implementation. Additionally, collaboration with industry stakeholders could strengthen curriculum relevance and provide authentic learning contexts for students. Future research may explore the long-term effects of AR-based training, comparative studies with other immersive technologies, and its scalability across different institutions and disciplines.

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