Augmented Reality Work Instructions for Electric Vehicle Maintenance Training: Skill Transfer and Retention

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Abstract.

Extending our evaluation of augmented reality (AR) in automotive vocational training, this study measures skill transfer and 90-day retention among 140 trainees learning electric vehicle (EV) battery-pack maintenance. The rapid growth of EV fleets in India has created demand for technicians able to service high-voltage battery systems safely, yet vocational institutes lack instructors with EV experience and the procedures carry safety risks that make unsupervised practice hazardous. AR work instructions, which overlay step-by-step guidance, component identification and safety warnings on the trainee's view of the physical battery pack, offer a potential solution. A two-arm experiment at three industrial training institutes in Delhi and Haryana assigned trainees to AR-guided instruction or to video-based instruction with printed manuals for a four-day battery-pack module covering isolation, module removal, cell balancing and reassembly. Skill transfer was assessed through a practical examination on an unfamiliar pack immediately after training, and retention through a repeat examination after 90 days, with safety errors recorded by blinded assessors. AR-guided trainees showed 24% higher retention with fewer safety errors than video-instructed peers: mean retention scores were 78.3 compared with 63.1, and the rate of critical safety errors was less than half that of the video group. Immediate transfer scores were also higher, though the difference was smaller. Training time did not differ between conditions. The findings indicate that AR work instructions support durable skill acquisition for high-voltage procedures and offer a practical route to scaling EV technician training where experienced instructors are scarce.

Keywords: augmented reality, work instructions, electric vehicle maintenance, skill retention, vocational training

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1. Introduction

India's transition to electric mobility is generating a shortage of technicians able to maintain high-voltage battery systems. Two- and three-wheeler EVs already account for a substantial share of new registrations (International Energy Agency, 2024), and fleet operators, dealerships and independent workshops report difficulty finding staff trained in battery-pack isolation, diagnosis and repair. Industrial training institutes, the backbone of vocational training in the country, are expanding EV curricula in response to national workforce projections (NITI Aayog, 2022), but they face two constraints. Instructors with practical EV experience are scarce, and battery-pack procedures involve electrical and thermal hazards that make unsupervised practice dangerous. Training methods that reduce dependence on expert instructors while maintaining safety are therefore of considerable practical interest.

In our earlier study (Kumar & Singh, 2025) we evaluated the efficacy of augmented reality in vocational training for automotive repair and found that AR-guided trainees completed conventional engine and brake procedures with fewer errors and reported higher confidence than trainees using printed manuals. That study measured performance immediately after training, and it examined procedures for which instructors were readily available. It left two questions open. First, does the advantage of AR persist over time, or does it reflect a temporary scaffolding effect that disappears when the overlay is removed? Second, does AR support safe performance on procedures with genuine hazard, where errors have consequences beyond a failed task?

The present study addresses both questions in the context of EV battery-pack maintenance. It compares AR work instructions with video-based instruction for a four-day module and measures skill transfer to an unfamiliar battery pack immediately after training, retention after 90 days and safety errors at both points. The study involves 140 trainees at three industrial training institutes and uses blinded practical assessment. Its contribution is evidence on the durability and safety of AR-supported skill acquisition in a domain of urgent workforce need, together with an analysis of which components of the procedure benefit most from AR guidance.

2. Literature Review

2.1 Augmented reality in industrial and vocational training

Augmented reality overlays computer-generated information on the user's view of the physical environment, and its application to assembly and maintenance has been studied for more than two decades. Henderson and Feiner (2011) demonstrated in a military maintenance setting that AR reduced the time spent locating components and the number of head movements compared with a display-based condition, and reported that technicians found AR more intuitive. Systematic reviews of AR in manufacturing and maintenance report consistent benefits for task completion time and error rate, particularly for novices and for procedures with many steps (Palmarini et al., 2018). In education and training, Radu (2014) synthesised evidence that AR improves content understanding and spatial skills while noting risks of attention tunnelling. Bacca et al. (2014) reviewed AR in education and found that vocational applications were among the most promising, though evaluation designs were often weak. Our own work (Kumar & Singh, 2025) added evidence from Indian vocational settings, where trainees have limited prior exposure to digital instruction, and found that AR was accepted readily.

2.2 Skill retention and the scaffolding problem

A recurring concern about instructional support is that it may improve immediate performance without producing durable learning. The guidance hypothesis in motor learning holds that frequent feedback or guidance during practice can create dependence, so that performance deteriorates when guidance is removed (Salmoni et al., 1984). Applied to AR, the concern is that trainees may follow overlays without encoding the procedure, and that retention may be poorer than for trainees who had to work harder from a manual. Empirical evidence is mixed. Webel et al. (2013) found that AR-trained technicians retained procedural knowledge at least as well as conventionally trained peers, while some studies report reduced retention when AR provides step-by-step guidance without requiring recall. The cognitive theory of multimedia learning (Mayer, 2009) suggests that AR benefits arise from spatial and temporal contiguity, since information appears where and when it is needed, reducing extraneous load; whether that reduced load supports or undermines encoding depends on whether trainees engage in generative processing. Sweller et al. (2011) note that instructional formats which reduce extraneous load free capacity for schema construction, provided the task itself demands it.

2.3 Safety in high-voltage maintenance

EV battery-pack maintenance involves voltages exceeding 400 V in many passenger vehicles and around 48 to 72 V in two- and three-wheelers, together with risks of thermal runaway if cells are damaged. Industry standards prescribe isolation, verification of zero energy and use of insulated tools and protective equipment before any intervention. Training research in high-hazard domains emphasises that procedural compliance, particularly the completion of verification steps that appear redundant, is the behaviour most often lost under time pressure. AR systems can enforce such steps by requiring confirmation before proceeding, a feature that Gavish et al. (2015) found reduced unsafe actions in an industrial assembly task. The present study treats safety errors as a distinct outcome from task accuracy and distinguishes critical errors, which would expose a technician to injury, from procedural errors, which would compromise the repair but not the person.

2.4 Hypotheses

Three hypotheses were tested. H1 proposes that AR-guided trainees achieve higher skill transfer scores on an unfamiliar battery pack immediately after training than video-instructed trainees. H2 proposes that AR-guided trainees show higher retention scores at 90 days, and that the retention advantage is at least as large as the immediate advantage, which would indicate that AR produces durable learning rather than temporary scaffolding. H3 proposes that AR-guided trainees commit fewer critical safety errors at both assessment points.

3. Methodology

3.1 Design and participants

A two-arm experiment with random assignment at the individual level was conducted at three industrial training institutes, one in Delhi and two in Haryana, between August 2025 and January 2026. Participants were 140 trainees enrolled in the final year of two-year automotive mechanic programmes, none of whom had prior training in EV battery systems. Trainees were stratified by institute and by prior practical examination score and randomly assigned to the AR condition (n = 70) or the video condition (n = 70). Table 1 presents the profile of the sample. All 140 completed training and the immediate assessment, and 134 (95.7%) completed the 90-day assessment, with attrition balanced across conditions. Ethical approval was obtained from IIT Delhi, and participants gave informed consent; training was conducted with de-energised packs under instructor supervision, and live high-voltage work was simulated with low-voltage training packs that replicated the procedure.

Table 1: Participant profile by condition (N = 140)

Characteristic	AR condition (n = 70)	Video condition (n = 70)	Total
Institute A (Delhi)	24	24	48
Institute B (Haryana)	23	23	46
Institute C (Haryana)	23	23	46
Mean age, years (SD)	20.4 (1.6)	20.6 (1.7)	20.5 (1.6)
Female trainees	9	8	17
Prior practical score, mean (SD)	71.2 (8.9)	70.8 (9.3)	71.0 (9.1)
Prior smartphone AR experience	31	29	60
Completed 90-day assessment	67	67	134

Source: Authors' experimental records (2026)

3.2 Training conditions and AR system

Both conditions covered the same four-day module on battery-pack maintenance for a two-wheeler and a small passenger vehicle: high-voltage isolation and verification, pack removal and opening, module and cell inspection, cell balancing and battery management system reconnection, and reassembly with insulation testing. Total instructional time was 24 hours in both conditions, with the same ratio of demonstration to hands-on practice. In the AR condition, trainees wore a head-mounted display running work instructions developed by the research team. The system used marker-based tracking on the training pack to overlay step numbers, component highlights, torque values, safety warnings and required tool identification, and it required trainees to confirm completion of each verification step by gesture before the next step was displayed. In the video condition, trainees viewed the same procedure on a tablet as a narrated video segmented by step, with a printed manual containing the same torque values and safety warnings, and were free to pause and replay. Instructors were present in both conditions to answer questions and supervise safety but did not demonstrate steps beyond an initial overview.

3.3 Measures

Skill transfer was assessed through a practical examination on a battery pack of a different model from those used in training, performed without AR or video support and with only a brief specification sheet. Trainees performed the isolation, module removal, cell balancing and reassembly sequence, and two assessors blind to condition scored performance against a 40-item checklist covering step completion, sequence, tool use and measurement accuracy, converted to a 0–100 scale. Inter-rater agreement was high (intraclass correlation 0.91). Retention was assessed by a parallel examination on a third pack model 90 days after training, during which trainees had returned to their regular curriculum without further EV instruction. Safety errors were recorded separately by the assessors and classified as critical, such as omitting zero-energy verification or handling a module without insulated gloves, or procedural, such as incorrect torque sequence. Completion time and a post-training questionnaire on confidence and perceived workload were also collected.

3.4 Analysis

Transfer and retention scores were compared across conditions with analysis of covariance controlling for prior practical score and institute, and effect sizes were computed as Cohen's d. Retention was also analysed as the change from immediate to 90-day score within each condition. Safety errors were compared with Poisson regression, and the proportion of trainees committing at least one critical error was compared with chi-square tests. Item-level analysis identified which procedural components showed the largest condition differences. Analyses followed the recommendations of Field (2018).

4. Results

4.1 Skill transfer and retention

Table 2 presents the transfer and retention results. Immediately after training, AR-guided trainees scored higher on the transfer examination than video-instructed trainees (81.6 versus 72.4, adjusted difference 9.0, $p < 0.001$, $d = 0.78$), supporting H1. At 90 days, both groups showed some decline, but the decline was markedly smaller in the AR group: retention scores were 78.3 for AR trainees and 63.1 for video trainees, an adjusted difference of 15.1 points ($p < 0.001$, $d = 1.12$). Expressed relative to the video group, AR trainees showed 24% higher retention. The retention advantage was larger than the immediate advantage, which supports

H2 and indicates that AR guidance produced durable learning rather than temporary scaffolding. The mean decline from immediate to 90-day assessment was 3.3 points in the AR group and 9.3 points in the video group. Completion time did not differ significantly between conditions at either assessment.

Table 2: Skill transfer and retention scores by condition (0–100 scale)

Outcome	AR condition mean (SD)	Video condition mean (SD)	Adjusted difference	p	Cohen's d
Immediate transfer (n = 140)	81.6 (10.2)	72.4 (12.1)	9.0	< 0.001	0.78
90-day retention (n = 134)	78.3 (11.4)	63.1 (13.7)	15.1	< 0.001	1.12
Decline, immediate to 90 days	3.3 (6.8)	9.3 (8.1)	−6.0	< 0.001	0.80
Completion time, immediate (min)	46.2 (8.7)	47.9 (9.4)	−1.7	0.27	0.19
Completion time, 90 days (min)	49.1 (9.3)	52.4 (10.8)	−3.3	0.06	0.33
Post-training confidence (1–5)	4.12 (0.61)	3.71 (0.74)	0.41	< 0.001	0.60

Source: Authors' experimental data (2026)

4.2 Safety errors

Table 3 reports safety errors. At the immediate assessment, AR trainees committed a mean of 0.31 critical errors per examination compared with 0.74 for video trainees, and 18.6% of AR trainees committed at least one critical error compared with 41.4% of video trainees. At 90 days the gap widened: the critical error rate was 0.42 per examination in the AR group and 1.06 in the video group, with 26.9% and 56.7% of trainees respectively committing at least one. Poisson regression confirmed that the condition difference was significant at both points ($p < 0.001$), supporting H3. The most common critical error in the video group was omission of zero-energy verification after isolation, a step that the AR system required trainees to confirm during training. Procedural errors also favoured the AR group, though the difference was smaller.

Table 3: Safety errors by condition and assessment point

Indicator	AR immediate	Video immediate	AR 90-day	Video 90-day
Critical errors per examination, mean	0.31	0.74	0.42	1.06
Trainees with ≥ 1 critical error (%)	18.6	41.4	26.9	56.7
Omitted zero-energy verification (%)	7.1	25.7	11.9	35.8
Procedural errors per examination, mean	1.9	2.7	2.4	3.6
Rate ratio, AR vs video (critical)	0.42		0.40	
p (Poisson regression)	< 0.001		< 0.001	

Source: Authors' experimental data (2026)

4.3 Component-level analysis

Item-level analysis showed that the AR advantage was concentrated in components with spatial complexity and safety-critical sequencing. The largest differences at 90 days were in the isolation and verification sequence, in identification of the correct module connector order and in the cell balancing procedure, each of which involves locating specific components and performing steps in a prescribed order. Differences were small for components that involve repetitive manual work, such as fastener removal and insulation testing, which trainees in both conditions performed comparably. Questionnaire data indicated that AR trainees reported lower perceived mental workload during training and higher confidence afterwards, and that confidence was correlated with retention in both groups.

5. Discussion

The study set out to determine whether the immediate advantages of AR guidance found in our earlier work (Kumar & Singh, 2025) persist over time and extend to safety-critical procedures. The answer on both counts is affirmative. AR-guided trainees showed 24% higher retention at 90 days, and the retention advantage exceeded the immediate advantage, which runs counter to the guidance hypothesis prediction that scaffolding produces dependence (Salmoni et al., 1984). The most plausible explanation is that the AR system used here did not merely display information but required active confirmation of verification steps and directed attention to the spatial location of components, which is consistent with Mayer's (2009) contiguity principles and with the argument of Sweller et al. (2011) that reduced extraneous load supports schema construction when the task demands it. Trainees appear to have encoded the procedure as a sequence of located actions rather than as a list to be recalled.

The safety findings are, from a practical standpoint, the most consequential. The omission of zero-energy verification is precisely the error that causes injury in high-voltage work, and the video group's rate of this omission at 90 days was three times that of the AR group. The result supports the finding of Gavish et al. (2015) that AR can enforce procedural compliance, and it extends it by showing that the enforcement leaves a trace after the system is removed. The widening of the safety gap over time suggests that the verification habit, once formed under AR guidance, is more resistant to decay than the same habit formed from video and manual instruction, where the verification step is easily skipped during practice because nothing prevents it.

The component-level analysis helps to specify where AR adds value. The advantage lay in spatially complex and sequence-critical components, not in repetitive manual work, which is consistent with reviews finding that AR benefits are greatest for procedures with many steps and for novices (Palmarini et al., 2018; Henderson & Feiner, 2011). This suggests that institutes need not convert entire curricula to AR; targeted use for the components that carry spatial and safety complexity may capture most of the benefit at lower cost. It also suggests a design principle for AR work instructions in training contexts: overlays should require confirmation of critical steps rather than simply displaying them, so that guidance becomes practice rather than substitution.

For Indian vocational training the findings have direct implications. The shortage of instructors with EV experience is unlikely to resolve quickly, and AR work instructions developed once by manufacturers or training authorities could be deployed across many institutes with supervising instructors who need not be EV specialists. The equipment cost of head-mounted displays remains a barrier, though smartphone-based AR is a lower-cost alternative that may deliver a portion of the benefit; roughly 43% of trainees in this sample had prior exposure to smartphone AR, which suggests acceptance would not be a problem. Concerns about digital instruction in populations with limited prior exposure, raised in reviews of AR in education (Bacca et al., 2014; Radu, 2014), were not borne out in this sample. The evidence that retention rather than immediate performance is the more sensitive outcome also argues for training evaluations, including those informing national skill certification, to include delayed assessment as standard.

6. Conclusion

This study measured skill transfer and 90-day retention among 140 vocational trainees learning EV battery-pack maintenance under AR work instructions or video-based instruction. AR-guided trainees achieved higher immediate transfer scores, showed 24% higher retention at 90 days with a substantially smaller decline, and committed fewer than half as many critical safety errors at both assessment points, with the largest differences in safety-critical verification steps. The findings extend our earlier evaluation of AR in automotive training by establishing that its advantages are durable and that they extend to hazardous procedures, and they support the use of AR work instructions as a means of scaling EV technician training where experienced instructors are scarce.

Limitations should be noted. The study used a single AR system whose design features, particularly mandatory confirmation of verification steps, may account for much of the effect, so results may not generalise to AR systems that display information passively. Training and assessment used de-energised or low-voltage packs, and performance under live conditions with real hazard may differ. The 90-day interval, while longer than most AR training studies, is shorter than the periods over which technicians must retain skills in practice. Future research should compare AR designs with and without enforced confirmation, test smartphone-based AR as a lower-cost alternative, extend retention assessment to six and twelve months, and evaluate workplace performance among graduates who enter EV service roles.

Acknowledgment

The authors thank the participating industrial training institutes and their trainees, and acknowledge support from IIT Delhi.

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