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### **Augmented Reality, Technical Training, and Workforce Productivity in Engineering Industries**

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#### **ABSTRACT:**

The study is a qualitative research, which uses the method to investigate the role of augmented reality in technical training and productivity of engineering industry labor. In-depth interviews with engineers, trainers and the users of the AR system were complemented with structured observations of AR-assisted training sessions and the systematic analysis of training materials. The participants were identified through purposive sampling and consisted of 24 participants who had first-hand, substantive experience with AR-based training applications. Thematic analysis was used to identify key patterns at the surface level in terms of learning efficiency, skill development, organizational and technical issues for AR implementation and operational productivity. The results show that augmented reality has a significant impact on increasing the speed of learning, decreasing error levels when performing a task, and increasing knowledge retention over traditional training methods. But there are challenges that can hinder the process, such as technology hardware limits, implementation cost, difficulty in developing content, and workforce resistance to technology. The study offers theory-based and action-oriented suggestions for engineering firms interested in using AR as an effective workforce development tool.

**Keywords:** Augmented reality, technical skills training, productivity in workforce, engineering industries, skill development, immersive learning, digital transformation, qualitative research

#### **INTRODUCTION:**

Digital technologies are spreading like wildfire within the engineering sector, driving a wave of change in industrial processes, working practices and organisational structures. One of these change-making technologies is augmented reality, which superimposes computer-generated perceptual information (visual, audio or haptic) onto a physical environment in real-time, allowing people to interact with both in tandem. In the realm of technical training and workforce development, AR has proven especially promising, and can help close the gap between the acquisition of knowledge and the practical skills that are currently lacking.

The engineering industries are defined by the complexity and criticality of their technical operations and include aerospace, automotive, civil and structural engineering, chemical processing, electrical systems and advanced manufacturing. The employees operating in each of these fields need to learn

and retain a wide range of specialized skills, perform complex multi-step processes with accuracy, and adapt to the ever-changing nature of the processes and their environment, which can often be dangerous. These competencies have been traditionally acquired through classroom training, paper-based manuals, demonstration via video, and supervised apprenticeship. But, as technology advances and competition in engineering industries intensifies around the world, there is growing recognition that these methods are becoming less effective in providing the rapid, large, and sophisticated skills development needs (Daling et al., 2020).

The limitations of training on a simulator are overcome in augmented reality by training through the real environment in which the equipment will operate, but without putting the trainee or equipment in danger. AR systems can incorporate step-by-step instructions, diagnostic feedback, safety warnings, and various expert comments directly onto the physical environment, providing workers with the informational support they need when completing complex tasks, and gradually decreasing the informational support as they become more proficient. The scaffolded learning approach is consistent with the pedagogical theories of Experiential Learning and ZPD that hold that learning is best achieved by engaging in guided practice in contexts that mirror the demands of real tasks (Dede, 2009).

In the last decade, the AR commercial and academic applications in industrial training have grown significantly since the convergence of display technology, spatial computing, computer vision and wireless technology. Pioneered in the field of augmented reality headsets, including the Microsoft HoloLens, Magic Leap, and an increasing number of industrial AR headsets, these devices now offer enough optical quality, processing speed and usability to support extended training applications in complex industrial settings. At the same time, the evolution of AR development platforms like PTC Vuforia, Scope AR and Atheer has significantly lowered the technical hurdles of creating AR content, allowing engineering organizations to build and publish their own customized training applications without having to hire AR software engineering professionals.

This progress notwithstanding, there is still relatively little systematic qualitative research on the role of AR in the learning experience of engineers and technical workers, on how AR co-exists with the current organizational learning cultures and systems, and on the organizational and contextual conditions that affect the success of AR. The dominant research approach in this domain has been quantitative, focusing on objective indicators of task completion time, errors, assessment scores, etc., that are affected by AR (Gavish et al., 2015; Webel et al., 2013). Such studies give important insights into the effects of learning in AR, but are weak in providing insights into the mechanisms, processes and contextual conditions that result in those effects, which are very qualitative in nature.

The purpose of this study is to fill this gap by conducting a qualitative study on the role of AR in technical training and productivity in the engineering industries. Based on in-depth interviews with engineers, trainers, and AR system users, along with observations of the training sessions and document analysis, the study examines the impact of AR on learning, skill development, and productivity results, as well as challenges of using AR in training. What are engineering professionals' perceptions and experiences of AR-based technical training? What is the effect of AR on the efficiency of learning and the development of skills? What are the implications of implementing AR for employees' productivity? What are the organizational and technical barriers for successful uptake of AR training?

This inquiry has implications beyond the academic realm. The shortage of skills in the engineering sector is a more severe problem in modern engineering industries around the world, due to the retirement of the experienced engineers, the fast pace of technology development, which makes it difficult to keep pace with the development of traditional training, and the increasing complexity of engineering systems that need interdisciplinary skills. However, without understanding the nuances of human and organizational learning and behavior in the context of technology-enabled learning, AR could prove to be just another tool in the tool box, and not the game-changer it promises to be. This study focuses on the lived experiences and professional judgments of engineering practitioners, thereby producing

contextually-situated knowledge that adds to and enhances the overall body of evidence on AR in industrial training.

## LITERATURE REVIEW:

### **The conceptual foundations and technological architecture of Augmented Reality**

The concept of augmented reality was originally categorized by Milgram and Kishino (1994) between the extremes of reality and virtuality. In this context, AR systems provide perceptual information generated by digital means to support the physical world, preserving the primacy of the physical world, but also introducing information and/or experience that extends the user's perception and interaction. The conceptual positioning makes AR different from virtual reality which fully replaces the physical reality, and different from mixed reality which allows more complex interaction between physical and virtual.

Technologically, the modern AR systems consist of three main architectural components: sensing and tracking systems that are used to sense and track the position of the system in space with respect to the physical environment, processing systems to compute and present digital content that can be correlated with that position, and the display systems that deliver the image on to the user. In the last decade, improvements have been made in each of the three components, to a significant degree, in terms of capability and usability of the AR system. There has been significant progress in spatial computing algorithms to achieve high accuracy in registration; in edge computing to achieve very low processing latency; and in optical waveguide display technologies to create lightweight, high fidelity see-through displays for sustained industrial use (Billinghurst et al., 2015).

There are three main ways of delivery for industrial AR applications: head-mounted display (HMD) AR, tablet/smartphone AR and projected AR, a type of AR that displays information directly on work surfaces or equipment without requiring the user to wear a device. All modalities have unique pros and cons regarding ergonomics, situational awareness, cost, and applicability to training programs, and choosing the appropriate delivery modality is a key design consideration for the development of AR training systems (Bottani & Vignali, 2019).

### **AR based Training in Engineering and Industrial Contexts**

The use of AR for training in industry has been studied in various engineering fields, and the results were generally positive, indicating that AR technology enhances task performance and skill acquisition. One of the first systematic reviews of AR-based maintenance training was carried out by Webel et al. (2013) who compared AR-based maintenance training to manual and video-based training for an assembly task. Their results showed that the people trained with AR were able to assemble the devices much faster and without the errors, and more easily recall the assembly steps at the follow-up assessment than were the people trained conventionally. These performance benefits were explained as the ability of AR to provide step-by-step and contextually relevant information, which decreases the cognitive load and the requirement for training attendees to split their attention between training materials and task environment.

Gavish et al. (2015) furthered this exploration by comparing AR- and VR-based training for complicated industrial maintenance tasks. They discovered that AR-trained workers exhibited a significantly higher transfer of training to the real environments of the tasks, which they attribute to the contextual fidelity of AR's preservation of the physical environment of the task. This transfer advantage is significant in practice for the engineering industry in which training results are assessed in real rather than simulated environments. The authors determined that a key strength of AR is its ability to maintain the physical task environment, especially when it comes to procedural skill training.

Wang et al. (2016) investigated the use of AR in aircraft assembly training where the AR-guided training methods proved to be effective in enhancing training efficiency and reduced error rates by 82 percent and training time by 35 percent when compared to traditional paper-based training methods in the aerospace manufacturing industry for complex multi-component assembly tasks. The extent of these performance gains is related to the specific types of engineering assembly tasks in which the AR has been found to be most effective, which are those tasks with spatial complexity and strict sequence requirements, where the AR's ability to present frame-by-frame, spatially registered, dynamic visual guidance is most valuable.

In addition to assembly and maintenance, AR has been used in training electrical systems, overlaying diagrams of the circuits, part identification data, and diagnostic decision trees into the physical electrical panels, allowing for safe and informative interaction with potentially dangerous equipment (Henderson & Feiner, 2011). For civil engineers, AR has been employed in visualizing and training subsurface infrastructure, which helps them visualize spatial relationships between utilities, structural elements, and the excavation area that are impossible to observe physically. The examples of the following pages demonstrate the unique ability of AR to make invisible or spatial information perceptually accessible that is applicable to engineering training environments broadly.

### **The pedagogical foundations of immersive and experiential learning**

The pedagogical merit of the AR-based training is supported by several learning theories, all of which highlight the importance of contexts, experiential, and cognitively efficient learning environments. The experiential learning theory of Kolb (1984) suggests that learning occurs most effectively when it is experienced, observed, conceptualized, and tested. The AR-based training naturally lends itself to this cycle, as it allows the learner to interact with real task environments, try out what they do, and incrementally experiment and develop mental models of the task domain.

Sweller (1988) developed cognitive load theory, which offers a strong theoretical basis to understand the advantages of instruction that AR offers. The theory separates the complexity of the content to be learned from the suboptimal design of the instructional content (extraneous cognitive load) and the mental effort required for schema construction (germane cognitive load). The concept of AR helps to remove the extraneous cognitive load by removing the requirement for learners to translate information from an external document or display to the physical task environment, allowing cognitive resources to be used for germane processing and schema construction. Daling et al. (2020) and van Krevelen and Poelman (2010) have validated this load reduction mechanism in empirical studies on the effects of AR training in research.

The pedagogical effectiveness of AR is complemented by situated cognition theory which states that "knowledge is a dependent variable of context, where context is the context of learning and the context of use" (Lave & Wenger, 1991). The classical form of learning or "documents" learning removes knowledge from its operational context, which reduces the applicability of the learned information to a given task in the real world. AR tackles this obstacle by integrating learning content directly into the physical operational context, which enables the learner to acquire situated knowledge representations that facilitate more easily appropriate to the actual task performance. The theoretical alignment of the technological features of AR with known learning science principles offers a compelling theoretical foundation for the observed empirical effectiveness of AR.

### **Workforce productivity and digital technology adoption important in engineering**

The impact of digital technology on the productivity of engineers' workers has been widely studied in operations management and human factors research. Every study has shown that technology-based performance support systems that deliver real-time task guidance, quality verification, and diagnostic assistance to workers at the point of performance can yield significant productivity gains by decreasing

work error rates, decreasing task completion times and allowing less experienced workers to perform at a level of capability that is close to that of expert practitioners (Funk et al., 2019).

AR is the most contextually integrated type of performance support technology—it provides informational content in line of sight, without causing a user to divert attention away from their task to other displays or documents. In manufacturing environments, task completion-time was reduced by 20-40% and error rate by 50-90% when using AR to work through a task than using conventional modalities of instructional support (Nee et al., 2012). Such productivity improvements are especially valuable in situations of high task complexity, long training periods, and high cost of mistakes in the engineering domain.

In the wider body of literature on the adoption of digital technology in engineering companies, the role of organisational readiness, the management of change and user acceptance as factors influencing the success of technology-driven productivity outcomes for the company are emphasized. Davis (1989) proposed a Technology Acceptance Model which identified perceived usefulness and perceived ease of use as two key factors affecting an individual's intention to use a new technology; this model is widely used in industrial applications of AR. Rese et al. (2017) used TAM to study the adoption of AR in the field of industrial AR, and their results showed that the perceived usefulness and ease of use of AR were significant predictors of the adoption intention of engineering workers, with ergonomic usability and task relevance as key factors affecting the utility of AR.

### **The major challenges and considerations to implementation**

Although AR has shown to be beneficial in terms of training and productivity, there are several technical, organizational and human factors issues identified in the literature that make its implementation in a context of engineering industry difficult. Despite all the technological advances, there are still technological limitations for use in challenging industrial environments, such as limited field of view, weight, comfort during long-term use, battery life, and sensitivity to ambient conditions like changing light and electromagnetic interference (Rambach et al., 2021).

Content development complexity and cost are a big organisational hurdle. Properly designing AR training content is a problem that requires a multidisciplinary approach, including instructional design, 3D modelling, software development and engineering knowledge of the subject matter, which is hard to find within a single engineering organization. Content maintenance is also challenging due to the quick rate of engineering process and equipment change, since underpinning engineering processes or equipment configuration changes make AR training content obsolete (Funk et al., 2019). They are development and maintenance costs, which are high economics, especially for small and medium size engineering companies.

In the literature, there are also reports of resistance from the workforce towards AR adoption, such as doubts regarding the real-world usefulness of AR, the use of wearable devices in the current working practices, or fears of surveillance and performance monitoring (Rese et al., 2017). Change management literature suggests that, besides being technically prepared, people have to be culturally ready to embrace change, which involves them being open to new innovations, building trust between employee and management, and communicating the benefits and constraints of new technologies. Engineering firms that overlook these human and organizational aspects of AR adoption often face obstacles to adoption that can impact the realization of the training and productivity gains of AR technology.

### **METHODOLOGY:**

To gain a deep understanding of the role of augmented reality in technical training and productivity of certain engineering industries, this study used a qualitative research approach. The study's main inquiry into the experience, interpretation and meaning-making of the engineering practitioners' use of AR-based training was decided upon with a qualitative approach as the most epistemologically appropriate

design for the study, as the phenomena being explored cannot be reduced to numerical measurement and requires interpretive exploration.

### **Research Design**

The study was interpretive phenomenological (IP) in nature, which was based on the premise that it is essential to gain access to the subjective experiences and professional interpretations of users of a technology to understand the impact of the technology on human learning and work performance. This orientation focused the research design on techniques that would facilitate the gathering of detailed, first-person narratives about AR training experiences, along with observational data and document analysis to triangulate and situate participants' accounts. The research was carried out in the past tense of action as required in qualitative research in the social sciences.

### **Sampling and Participants**

The choice of purposive sampling was made to identify and recruit participants who have direct and substantive experience in AR-based applications of training in engineering industrial settings. Selection criteria included direct experience of AR training as an engineer, trainer or trainee for at least 6 months, to limit exposure to accounts that had been built on sustained experiential knowledge. Twenty-four members of engineering organizations in the aerospace, automotive, civil, chemical and electrical engineering fields were recruited in total. The participants consisted of eight practicing engineers who have participated in AR-based training courses, eight engineers working as technical trainers, developing and providing AR training, and eight trainees who are currently undergoing AR training courses. Recruitment was continued until saturation was reached theoretically.

### **Data Collection**

Three complementary strategies for data collection were used. Primary data collection involved conducting individual, semi-structured in-depth interviews via videoconference or in person at the interviewees' workplace, and lasted for 60-90 minutes. The interview guide included questions on the participant's previous training experiences, evaluation of the instructional effectiveness of AR, the impact on skills and productivity, and barriers to implementation. Informed consent was obtained and interviews were audio recorded and transcribed verbatim.

Secondary data were collected from structured observation of AR-assisted training sessions that were observed at four selected engineering organizations. The durations of each observation were between 90 and 3 hours in length, and field notes were taken in as much detail as possible, including trainer behaviors, trainee interactions with AR systems, potential training blockages and misunderstandings, and contextual factors affecting the delivery of the training. In addition, the training materials such as AR content specifications, competence profiles, assessment instrument and post training evaluation records were analyzed systematically to triangulate the results of the interviews and observations by supporting the documentary approach.

### **Data Analysis**

The main analysis method used was thematic analysis based on the six phases outlined by Braun and Clarke (2006). The analysis was initiated by familiarisation with the data, re-reading the verbatim transcripts and checking the field notes; followed by open coding the data for salient data features; then clustering data features into candidate thematic categories; then review and refinement of themes; then final theme definition and naming; then generation of an interpretive account that concluded with an integrated analysis of the primary and secondary data sources. NVivo software, a qualitative data analysis program, was used for the analysis. We maintained a reflexive research journal noting methodological decisions and interpretive assumptions as we worked our way through analysis and

used the process of peer debriefing and member checking with a subset of participants to provide analytical rigor.

**Ethical Considerations**

Ethics approval was received from the institution before collection of data. Written informed consent was obtained and anonymity and confidentiality of all participants were ensured, and they were given the freedom to withdraw at any time, without penalty. All research outputs included organizational data were anonymized. The training managers and all people in the observed sessions consented to the collection of observational data.

**ANALYSIS AND FINDINGS:**

The analysis of interview transcripts, observational field notes, and training documents resulted in five main thematic categories: Enhanced Learning Efficiency Through Contextual Guidance; Accelerated Skill Development and Knowledge Retention; AR-Driven Workforce Productivity Gains; Implementation Challenges and Adoption Barriers; and Organizational and Cultural Dimensions of AR Integration. These themes are further detailed with illustrative evidence from the participant commentaries, observations and the documentary evidence.

**Theme 1: Improved Learning Efficiency by providing Contextual Guidance**

The most frequent learning experience transformation identified for AR that was reported was the removal of attentional splitting between the task environment and the instructional materials. In every group of participants, interviewees relayed their experience of having to refer to manuals and diagrams or a video screen during conventional training while also trying to perform physical tasks—a divided attention demand that slows down performance and led to higher error rates. AR's ability to provide contextually located, spatially registered guidance directly in the field of view of the task has been reported to be a paradigm shift in the cognitive experience of learning a skill.

This change was especially well illustrated by a senior trainer in the aerospace industry, who stated that, compared to the industry's traditional methods of assembly training using two-dimensional schematics, trainees with AR-based assembly guidance did not have to mentally translate the two-dimensional instructions to three-dimensional actions, one of the most severe cognitive challenges in aerospace assembly training. However, the spatial registration of AR guidance to the actual components removed this translation requirement, and allowed trainees to concentrate cognitive resources on the understanding and execution of the procedure.

The information obtained from the observations was supported by information from the interview. In all observed AR training sessions, trainees showed greater fluency and continuity in task execution and fewer procedural interruptions during AR sessions than during sessions in which the instructional supports were conventional paper or screen based. Average instructional reference interruptions were significantly reduced in AR-supported conditions, and there were significantly fewer occurrences of discernible confusion or hesitation in procedural steps by trainees.

**Table 1: Participant-Reported Learning Efficiency Improvements by Engineering Sector and AR Application**

Engineering Sector	AR Application	Training Time Reduction	Error Rate Reduction	Key Efficiency Mechanism
Aerospace	Assembly guidance	32–40%	74–82%	Spatial registration of steps
Automotive	Engine maintenance	28–35%	65–78%	Contextual component ID



Electrical Engineering	Panel wiring & diagnostics	25–33%	70–80%	Circuit overlay visualization
Chemical Processing	Plant operations training	20–30%	55–68%	Safety annotation overlays
Civil Engineering	Subsurface utility training	18–27%	48–62%	Invisible infrastructure viz.

**Theme 2: Accelerated Skill Development and Knowledge Retention**

Participants all indicated that the AR method of training allowed them to progress more quickly towards meeting the standards of operational competency than traditional training methods. Engineers who had gone through AR training programs reported that they were able to master complex maintenance and assembly tasks where they were used to doing these tasks for many hours in the past, but now they are able to do it in fewer hours and with a higher percentage of success.

Knowledge retention was a very surprising result. Several of the participants reported that the spatial and contextual embedding of the procedural knowledge into the physical task environment using AR led to more robust and persistent memory traces than abstract instructions. In the study, a technical trainer in the automotive industry commented that trainees that have been trained in AR-based engine maintenance techniques outperform the ones who have been trained using the same engine maintenance video content in one-month and three-month assessments and noted that this is due to the rich multi-sensory experiential encoding that AR enables.

These qualitative accounts were supplemented by documentary evidence from training assessment records from the three organisations involved. Consistently higher scores on post-training competency assessment were found for the AR-trained cohorts compared to contemporarily-trained cohorts (traditional training) across all three organizations. Follow-up retention assessment data from two organizations showed that the AR advantage in knowledge retention continued and, in some instances, increased at the 3-month assessment time point, suggesting that AR's memory encoding advantages do not diminish over time via forgetting.

**Table 2: Skill Development and Knowledge Retention Outcomes — AR vs. Conventional Training**

Outcome Measure	Conventional Training	AR-Based Training	Improvement	Participant Attribution
Time to operational competency	Baseline (100%)	Reduced 28–38%	Significant	Contextual scaffolding
Post-training assessment score	Baseline (100%)	+18–26%	Moderate–large	Richer encoding
3-month retention assessment	Baseline (100%)	+22–31%	Large	Situated memory traces
First-attempt task success rate	54–68%	79–91%	+25–37 pts	Embedded guidance
Supervised repetitions to proficiency	8–14 cycles	4–7 cycles	~50% reduction	Load reduction

**Theme 3: AR-Driven Workforce Productivity Gains**

In addition to training benefits, participants reported significant gains in productivity as a result of the implementation of AR in their work environments. In the operational tasks where engineers used AR for performance support (not just for training), the engineers reported significant improvement in task completion time, error rates and the incidence of having to seek supervisory support. These productivity

gains were most frequently reported in infrequently performed, high complexity tasks, which have the highest cognitive demands on procedural recall and the highest consequences for error.

A chemical process equipment shutdown and maintenance process engineer explained how AR had helped to significantly shorten planned process equipment shutdown and maintenance times. The AR system offered step-by-step, spatially registered procedural help for infrequent but highly complex maintenance activities for less-experienced technicians, eliminating the need for a few practitioners to do the work and therefore increasing the overall flexibility of operations.

Trainers saw that AR's productivity advantages also related to the training delivery process itself. The AR-based training systems provided a lower trainer/trainee supervision needed for safe and effective procedure training, allowing training departments to scale training delivery without a proportional increase in trainers. Several training managers spoke about how AR had turned training from an activity of a few individuals that needed a lot of resources and supervision, into a learning process that could be scaled-up and done semi-autonomously, with trainers being able to observe several trainees and intervene at targeted points as they actually needed it, if they were aware of the learning difficulty.

**Table 3: Workforce Productivity Outcomes Attributable to AR Implementation**

Productivity Dimension	Pre-AR Baseline	Post-AR Outcome	Change (%)	Application Context
Maintenance task completion time	Baseline	Reduced	-22 to -40%	Complex equipment MRO
Operational error rate	Baseline	Reduced	-55 to -80%	Assembly & wiring tasks
Supervisory escalation frequency	Baseline	Reduced	-45 to -60%	Novel & infrequent tasks
Trainer-to-trainee ratio required	1:2 to 1:3	1:5 to 1:8	+150%	AR-supervised training
Planned maintenance outage duration	Baseline	Reduced	-18 to -30%	Process plant shutdown
Rework and correction time	Baseline	Reduced	-60 to -75%	Precision assembly

**Theme 4: Implementation Challenges and Adoption Barriers**

However, despite the consistently positive training and productivity results reported, participants were able to identify several major challenges to the implementation that had complicated and/or constrained AR initiatives in their own organizations. The most common technical challenges were hardware constraints. Participants mentioned challenges such as limited optical field of view, affecting spatial awareness when performing tasks; weight, which was uncomfortable and caused fatigue when worn for longer training sessions; and battery life, which was a constraint during longer training sessions. Some participants indicated that the ergonomic restrictions were especially challenging in the physically demanding engineering setting where the worker must assume a difficult body stance or work in a restricted area.

The main organizational challenge was the cost and complexity of content development. Trainers and training managers expressed the significant amount of time, expertise and financial resources needed to create high quality AR training content for complicated engineering processes. The development of AR content involved multiple disciplines, including subject matter engineers, instructional designers, 3D modelers, and software developers, who needed to work concurrently, leading to coordination issues and dependency bottlenecks that slowed down development and raised costs. Some of the participants

estimated that the cost for developing AR content is 5-10 times higher than the cost of developing equivalent conventional training content.

In several organisations, workers voiced resistance, especially regarding the ability of the AR guidance to help them with tasks they believed they were already familiar with. In some work settings, data collection on AR devices such as data from the eyes and video capture of operational environments raised privacy issues as well. Evidence from the observations showed that skilled technicians sometimes abandoned AR systems while working on a task and used a manual approach instead, which was considered a recurring issue for the adoption of AR systems by trainers and was definite for deliberate change management.

**Table 4: AR Implementation Challenges, Frequency, Severity, and Mitigation Approaches**

Challenge	Category	Cited by (n=24)	Severity Reported	Mitigation Approaches
Hardware ergonomic discomfort	Technical	21	Moderate–High	Lightweight HMD selection; session limits
Restricted field of view	Technical	19	Moderate	Task-specific HMD selection
Content development cost	Organizational	23	High	Modular templates; vendor platforms
Content maintenance burden	Organizational	20	Moderate–High	Agile content update workflows
Workforce resistance / skepticism	Human	18	Moderate	Co-design; champion programs
Privacy and data concerns	Human / Legal	14	Moderate	Data governance policies
IT integration complexity	Technical	16	Moderate	API-based system integration
Battery life limitations	Technical	17	Low–Moderate	Charging station provision; modular sessions

**Theme 5: Organizational and Cultural Dimensions of AR Integration**

The fifth theme integrates the results on the organizational and cultural conditions that influenced the implementation outcomes of ARs in the participating engineering organizations. Organizational leadership commitment was consistently cited as the strongest predictor of the success of implementing AR. Organizations with strong leadership from senior engineering executives that provided sufficient resources and a clear rationale for investing in AR experienced much more positive outcomes of implementation than organizations that attempted AR as a secondary technology initiative without executive support.

A secondary but important factor was the role of the organizational learning culture. Organizations with high levels of psychological safety, encouragement of experimentation, and tolerance of the performance dips associated with technology transitions were associated with participants' reports of smoother and more rapid AR adoption trajectories than were organizations with psychologically unsafe cultures, error-averse cultures, and cultures of performance accountability. The trainers who worked at organizations in the first category said that the engineering workers were more willing to be open with AR systems, recognize the problems, and persevere through the learning curve curve of accepting new AR interfaces.

The participants also indicated the need for the incorporation of engineering workers in the design and content development of the AR system. Organizations that used co-design processes (with experienced engineers specifying and reviewing AR training content) experienced greater user acceptance, more contextually appropriate content, and less cumbersome implementation processes than those that created AR training content from centralized teams of instructional designers without practitioner involvement. The findings are consistent with existing user-centered design principles and underscore the need for the practitioners' professional knowledge and skills to ensure that AR training content is appropriate to the context of engineering task performance.

**Table 5: Organizational Factors Influencing AR Training Implementation Outcomes**

Organizational Factor	Influence Direction	Evidence from Participants	Strategic Recommendation
Executive leadership sponsorship	Strong positive	Cited by 22/24 as critical	Appoint senior AR champion
Organizational learning culture	Positive	Safety to experiment essential	Cultivate psychological safety
Practitioner co-design involvement	Positive	Higher acceptance & accuracy	Embed engineers in content dev.
Change communication quality	Positive	Reduced skepticism & resistance	Transparent, benefit-led messaging
Dedicated AR support resources	Positive	Faster issue resolution	Establish AR centre of excellence
Workforce change resistance	Negative if unmanaged	Experienced worker disengagement	Early engagement; champion networks

**DISCUSSION:**

This study's results offer a theoretically consistent and empirically grounded analysis of the transformative potential of AR in the context of technical training and workforce productivity in engineering industries, as well as shed light on the conditions of the organization and technology that will control how that potential is realized. Overall, these five thematic findings support AR's congruence with the already known tenets of cognitive load theory, situated cognition, and experiential learning, and also bring to the fore some contextual insights into how AR works and how it provides effective training in complex industrial environments.

The results of the learning efficiency and skill development that were presented in Themes 1 and 2 are very similar in terms of the conclusions that can be drawn from the results of the existing experimental literature on AR in industrial training. The quantitative results obtained by participants (28-40% reduction in training time, 55-82% reduction in number of errors, and 22-31% improvement in retention assessment compared to traditional training) are generally in line with those reported in previous controlled studies (Gavish et al., 2015; Wang et al., 2016). The explanatory role of the qualitative data in this evidence base supports the idea that the required instructional conditions that help deepen schema formation were isolated as theoretically coherent mechanisms that align with the predictions made by the cognitive load theory regarding how to scaffold schema formation over time.

Apart from the training domain, the research contributions of the workforce productivity findings in Theme 3 expand the research to the question of the operational impact of AR. Interoperability and the reporting of enhancements in the efficiency of maintenance tasks, error rates, and the frequency of escalation to the supervisor in operational contexts (not just training contexts) indicate that AR can be used as an effective tool on the engineering competency development continuum, from skill acquisition to expert practice. The discovery has broad strategic relevance for engineering firms interested in

investing in AR, meaning that AR's productivity benefits do not end in the training process, but continue to be realized in ongoing operational performance benefits.

The findings for the challenge of implementation in Theme 4 are significant practical contributions to the AR adoption literature. Optimistic stories about hardware improvements to facilitate AR adoption are now the top-ranked and most often cited challenge to the acceleration of AR adoption, given that content development cost/complexity is the major challenge cited, and not hardware issues. While hardware is getting better, there are still solutions that need to be provided at the organizational, educational and market level: Technical complexity reduction of AR authoring tools, expansion of the AR content development services market and capability development of organizations in AR instructional design.

The organizational and cultural results in Theme 5 are perhaps the most distinctly qualitative in the study, bringing to light the human and institutional aspects of AR implementation that quantitative studies of outcomes are unable to access. By identifying organizational learning culture as a significant moderator of AR adoption outcomes, the study extends the technology acceptance literature by placing individual attitudes toward the adoption of AR in the broader context of the organizational learning culture that affects them. An engineering organisation that focuses solely on technical aspects of AR, without considering the cultural environment that makes effective use of the technology, may be risking underperforming their AR investments.

#### **CONCLUSION AND RECOMMENDATIONS:**

This qualitative study has explored the potential application of augmented reality in enhancing technical training and workforce productivity in engineering industries by analyzing the views of twenty-four engineers, trainers and AR-system users along with the observations of structured training sessions and the documentary analysis. The findings of the research can be summarized in five thematic findings that, taken as a whole, show AR's potential to reshape the effectiveness of technical training, to speed up skill acquisition, to increase knowledge acquisition, to increase the productivity of the workforce, and to reveal the conditions that accompany these capabilities.

The overarching message is that AR is a truly transformative training and performance support technology for engineering sectors, and offers advantages in terms of training efficiency, speed of learning, at which learning takes place, and the durability of knowledge retained, as well as a reduction in operational errors and the scalability of training. These benefits however, do not happen by default when technology is implemented. The quality of the AR content development, the organizational culture in which AR is developed, the organizational change management strategies used to successfully implement AR to a workforce, and the continuous organizational leadership commitment to AR as a strategic workforce development investment are key elements and drivers that they rely heavily on.

Another finding, though not as significant, was related to the operational rather than instructional productivity of AR. However, the proof that AR benefit during real engineering tasks leads to significant gains in task efficiency, error rates and operational flexibility implies that engineering companies should consider the value proposition of AR in the entire operational process from training to expert support, not just in terms of training program outcomes.

#### **RECOMMENDATIONS:**

Engineering organizations considering or scaling out AR training programs are encouraged to consider AR adoption strategies as part of workforce development initiatives, not technology initiatives. Sponsorship from the Executive team should be secured at the beginning and Governance should be in place to ensure accountability for technical implementation quality and organizational change management. Co-designing with practitioners should be integrated in AR content creation to maintain the contextual accuracy and user acceptance. For continuous content maintenance resources,

organizations should allocate resources according to the rate of engineering process and equipment change in their operating environment.

For AR technology developers and AR platform providers, on-going investment in developing authoring tools that requires less technical skills for AR content creation is strongly recommended. Organizations would have less need to rely on single-vendor solutions, and the economics of adoption of AR technology would be improved for small and medium-sized engineering companies if there were interoperability standards to allow for AR content deployment on various hardware platforms. Head-mounted AR displays with better ergonomic design for industrial environment is still a key objective of hardware development.

Engineering education institutions could fill the talent need for implementing AR by including AR literacy competencies and AR content development competencies in engineering and technical training curricula. The ability of the industry to quickly gain adoption and productivity improvements would be accomplished by policymakers investing in the adoption support programs for small and medium-sized engineering enterprises, such as subsidized content development services, shared AR content repositories, and AR implementation advisory services.

This study's limitations can be improved in future research through the adoption of longitudinal designs that are able to capture the training and productivity impacts of AR over time at operational time scales. A comparative case study research that includes the analysis of organizational cultural and leadership variables that influence the results of AR adoption in various engineering sectors would enrich the theoretical framework for predicting and designing effective AR implementation strategies. Future research to operationalize the themes of the constructs identified in this study, and to test their relationships with objective productivity measures, would be useful for providing complementary evidence and increasing the generalizability of the findings presented here.

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