



Immersive learning in aviation: Integrating virtual, augmented, and mixed reality into cabin crew training

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ABSTRACT

This study examines how immersive technologies, including virtual, augmented, and mixed reality, can enhance cabin crew training and operational readiness in civil aviation. Drawing on established learning theories, the research investigates how immersive environments improve procedural accuracy, situational awareness, crisis management, and teamwork compared with traditional classroom and simulator-based instruction. A phenomenological design based on in-depth semi-structured interviews with 30 active cabin crew members served as the primary methodological approach, supported by a systematic review of prior studies on extended reality applications in aviation. The interviews provided detailed insights into participants' perspectives on immersive training, revealing how these technologies foster confidence, coordination, and preparedness for high-pressure flight scenarios. The findings show that immersive environments enable realistic and repeatable crisis simulations that strengthen both cognitive and behavioral learning outcomes, while also highlighting challenges related to equipment access, user comfort, and simulation fidelity. Sustainable integration requires ongoing instructor development, investment in high-quality infrastructure, and clear regulatory guidance. The study contributes to aviation management by demonstrating that incorporating immersive technologies into cabin crew education strengthens safety culture, enhances workforce digital proficiency, and supports the long-term professional development of aviation personnel.

1. Introduction

Cabin crew training is central to civil aviation safety and service quality, ensuring that airline personnel can manage both routine operations and emergency situations effectively (Larrea et al., 2022; Folke and Melin, 2024). Traditionally delivered through classroom instruction, procedural demonstrations, and full-scale cabin simulators, such training provides essential technical knowledge but continues to face persistent constraints. High operational costs, limited scenario diversity, and difficulties in recreating rare or high-risk emergencies with psychological realism restrict its effectiveness (Bagassi et al., 2018; Thomas et al., 2021). These challenges have encouraged aviation educators, regulators, and airlines to explore alternative learning approaches that complement existing simulator-based frameworks.

Recent advances in immersive technologies have begun to reshape

aviation education (Miani et al., 2021). Extended Reality (XR), which includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), enables the integration of theoretical instruction with interactive, high-fidelity simulation (Cipresso et al., 2018; Jerald, 2016; Milgram and Kishino, 1994; Jiang et al., 2023). AR and MR project digital information into the physical environment, providing real-time procedural guidance and contextual cues that support active learning (Peng et al., 2022). VR immerses trainees in computer-generated settings where complex emergencies can be rehearsed with realistic sensory engagement (Bailey et al., 2017; Zmigrodzka and Kostur-Balcerzak, 2018). These technologies enable training situations that more closely reflect operational conditions in a safe and controlled manner. For example, AR and MR can visualize cabin layouts and safety equipment, while VR allows learners to combine theoretical understanding with practical application within a virtual cabin (Borgen et al., 2021).

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Repeated exposure to emergency procedures (e.g., passenger evacuation) has been shown to improve both procedural accuracy and emotional readiness under stress.

Despite this technological progress, academic research on cabin crew training remains limited. Many studies examine AR, MR, or VR separately, which obscures their comparative value and the pedagogical potential of integrated use (Cross et al., 2023; Wu and Vu, 2022). In contrast to the extensive literature on pilot training, empirical research on cabin crew development is comparatively scarce, even though this role requires a distinct combination of safety, service, and psychological competencies (Auer et al., 2021; Kaplan et al., 2021). In addition, few investigations adopt comprehensive theoretical perspectives to explain how immersive learning contributes to procedural precision, cognitive processing, stress management, and long-term retention (Merchant et al., 2014; Radianti et al., 2020). These gaps limit both theoretical advancement and the development of evidence-based guidance for regulators and training managers seeking to modernize aviation education.

This study addresses these limitations through a comparative and theoretically grounded investigation of how AR, MR, and VR can be integrated to enhance cabin crew training. Drawing on behaviorist, cognitivist, constructivist, experiential, and social learning perspectives (Hays, 2006; Hollerer and Schmalstieg, 2016; Jerald, 2016), the research examines how these immersive modalities, individually and collectively, influence knowledge acquisition, procedural performance, and learner motivation. It also builds on the historical, institutional, and psychological foundations of cabin crew education (Cowper and Buerger, 2003; EASA, 2017; IATA, 2020), situating the analysis within evolving aviation safety and training standards. This framework clarifies how immersive environments can improve learning outcomes while reinforcing safety culture and supporting the development of a digitally competent aviation workforce.

Accordingly, this study addresses the following research question: *How do XR-based immersive learning environments enhance cabin crew training by supporting knowledge development, procedural accuracy, crisis management, and learner motivation in civil aviation?*

To investigate this question, the study explores how immersive training environments contribute to the development of operational competence by enabling cabin crew to translate abstract safety principles into practical action in high-stakes aviation contexts. This examination is informed by qualitative insights and prior empirical evidence on technology-enhanced learning.

This study contributes to both aviation management and educational technology literature by establishing a conceptual link between the pedagogical capabilities of AR, MR, and VR and learning processes that underline effective training performance. It provides comparative empirical evidence on the relative strengths and limitations of each technology and their combined use in safety-critical, team-oriented environments. In addition, the study offers practical direction for airlines, aviation academies, and regulatory authorities seeking to design cost-effective and scalable curricula that remain aligned with aviation safety standards while incorporating immersive technologies (Boeing, 2022; Moesl et al., 2022). Consolidating fragmented technology-focused research within a coherent pedagogical perspective advances understanding of technology-supported aviation education and offers insights that can strengthen cabin crew preparedness, safety performance, and professional development in increasingly digital training environments.

2. Conceptual framework

The integration of AR, MR, and VR into cabin crew training requires a clear understanding of their technological features and the learning theories that explain how they foster educational outcomes. AR enriches the physical environment by overlaying digital elements (e.g., graphics, text, or three-dimensional objects) onto real settings. MR advances this process by enabling digital and physical components to interact in real

time so that trainees can handle virtual objects as if they were tangible (Milgram and Kishino, 1994; Peng et al., 2022). VR differs by immersing users in fully computer-generated environments that provide visual, auditory, and tactile feedback, replicating flight conditions with a high degree of realism (Jerald, 2016; Zmigrodzka and Kostur-Balcerzak, 2018). Together, these technologies overcome key limitations of traditional instruction, which depend heavily on lectures and fixed simulators that are expensive and limited in reproducing the stress, unpredictability, and procedural complexity of in-flight emergencies (Bagassi et al., 2018; Thomas et al., 2021). XR creates realistic and repeatable learning environments that mirror operational challenges in a safe and cost-efficient manner by integrating real-time contextual guidance with immersive simulations (Bailey et al., 2017; Cipresso et al., 2018).

Aviation education encompasses a range of interrelated learning processes that demand procedural accuracy, cognitive discipline, experiential involvement, and coordinated teamwork under pressure. These dimensions are closely connected in real operational settings, and no single theoretical lens can fully account for their interaction and complexity. The application of multiple learning theories in this study is intentional rather than eclectic, reflecting the layered and integrated nature of aviation learning. Behaviorist principles emphasize the importance of repeated practice and reinforcement in developing procedural competence, cognitivist approaches explain how information is processed and retained, constructivist and experiential perspectives highlight reflection and adaptive problem solving, and social learning theory focuses on observation, collaboration, and shared understanding. Together, these perspectives provide a coherent theoretical foundation for explaining how immersive technologies enhance the procedural, cognitive, experiential, and social dimensions of cabin crew competence.

In line with this foundation, the behaviorist approach has particular relevance to aviation contexts that depend on procedural precision. It views learning as the gradual strengthening of stimulus and response associations through structured practice and timely feedback (Skinner, 1938; Watson, 1913). Many operational duties, including safety demonstrations, evacuation drills, and decompression management, require automatic responses refined through repetition. VR environments provide opportunities for trainees to rehearse these procedures while receiving immediate corrective input that enhances procedural memory and consistency (Auer et al., 2021; Hays, 2006; Kaplan et al., 2021). AR and MR further support this process by presenting sequential prompts and contextual guidance during live exercises, reinforcing correct performance in real time (Peng et al., 2022). Consistent with Gagné's (1965) principles of effective instruction, immersive technologies serve as reinforcement systems that strengthen procedural accuracy and performance reliability through continuous feedback and practice.

The cognitivist approach, grounded in information processing theory, examines how learners acquire, organize, and retrieve information while managing cognitive load (Bruner, 1966; Gagné, 1965). Cabin crew members must process multiple instructions and make rapid decisions in high-stress situations, which can strain working memory. AR and MR help reduce extraneous cognitive load by embedding cues directly into the environment (e.g., displaying procedural instructions on emergency exits or control panels), thereby enhancing recall and supporting schema formation (Borgen et al., 2021; Gangabissoon et al., 2020). VR complements this by transforming abstract principles, including the effects of cabin pressure loss or hypoxia, into vivid sensory experiences that deepen understanding and retention (Dymora et al., 2021; Merchant et al., 2014; Wu and Vu, 2022). Immersive environments promote meaningful learning and improve information retrieval in complex, time-sensitive operations through closer alignment with cognitive structures.

From a constructivist and experiential learning perspective, knowledge is developed through active participation, critical reflection, and adaptation to authentic experiences (Kolb, 1984; Piaget, 1970). Trainees

learn more effectively when they engage in realistic problem-solving and reflect on their actions. AR-based exercises require learners to interpret contextual cues, assess risks, and make informed decisions. Similarly, VR environments expose them to realistic emergency scenarios that allow exploration, reflection, and adaptation. These experiences lead to deeper conceptual understanding and situational judgment (Radianti et al., 2020; Safi and Chung, 2021). Consistent with Kolb's learning cycle, which includes concrete experience, reflective observation, abstract conceptualization, and active experimentation, VR promotes iterative learning that fosters adaptability, self-efficacy, and emotional control (Bailey et al., 2017; Hays, 2006). Such experiences encourage independent thinking and prepare crew members to respond effectively to unpredictable situations.

The social learning perspective highlights the cooperative and interactive character of aviation work. Bandura (1986) and Vygotsky and Cole (1978) maintain that individuals learn through observation, modeling, and collaboration within social contexts. Crew resource management depends on communication, leadership, and shared situational awareness, which can be effectively cultivated through immersive group exercises. Multi-user AR and VR platforms allow pilots and cabin crew to coordinate responses to simulated emergencies, observe expert performance, and engage in shared reflection (Moesl et al., 2022; Weelden et al., 2021). These collaborative environments strengthen interpersonal communication, teamwork, and collective problem-solving. AR and VR facilitate the development of shared mental models essential for cohesive and effective crew performance by offering psychologically safe spaces for experimentation and feedback.

Collectively, these theoretical perspectives show that the integration of AR, MR, and VR technologies provides a comprehensive and effective framework for aviation education. AR and MR enable context-based learning that enhances procedural precision and cognitive clarity, while VR offers immersive experiences that reinforce behavioral mastery and collaboration. The combined application of these technologies addresses all dimensions of professional learning, including procedural, cognitive, experiential, and social aspects, and establishes a robust theoretical basis for advancing the modernization of aviation training. Table 1 summarizes how each learning theory aligns with key learning mechanisms, the distinct functions of AR, MR, and VR, and the resulting outcomes for cabin crew training.

3. Methodology

3.1. Research model and design

This study adopts a phenomenological research design to examine how cabin crew trainees and instructors experience the use of immersive technologies in aviation training. This approach enables exploration of participants' lived experiences and provides insight into observable behaviors as well as the cognitive and emotional processes (e.g., engagement, confidence, and adaptation) associated with immersive systems (Moustakas, 1994; Neubauer et al., 2019).

The research model is informed by educational perspectives that link procedural mastery, cognitive processing, experiential reflection, and collaborative learning. These foundations shaped the study framework, guided the development of the interview protocol, and informed the interpretation of the data. Within this framework, XR technologies are treated as interactive learning environments that enable practice, reflection, and shared understanding among trainees and instructors.

Data were collected through an initial open-ended questionnaire followed by semi-structured interviews and analyzed using an interpretive approach suited to capturing detailed experiential accounts while maintaining methodological rigor. Such a design is particularly appropriate for emerging technologies, where standardized measurement tools remain limited and experiential insights provide the primary basis for understanding (Webster and Watson, 2002; Wolfswinkel et al., 2013). The study seeks analytical rather than statistical generalization by identifying patterns and themes that explain how immersive learning environments influence motivation, confidence, situational awareness, and collaborative problem solving. This approach contributes to understanding how immersive technologies reshape learning processes and support safety culture in aviation training (Safi and Chung, 2021; Zmi-grodzka and Kostur-Balcerzak, 2018).

3.2. Participants and sampling

Participants were selected through purposive sampling to capture experiences and perspectives directly relevant to the study's objectives. In line with qualitative research principles, the strategy focused on information-rich cases capable of generating analytically meaningful and practice-informed insights into immersive learning rather than statistical representativeness.

The final sample consisted of 30 actively flying cabin crew members employed by both flag-carrier and low-cost airlines in Turkey. This composition introduced variation in operational settings, corporate

Table 1
Conceptual framework linking learning theories, immersive technologies, and training outcomes.

Learning theory	Core mechanisms of learning	Key role of AR/MR/VR	Targeted training outcomes	Key sources
Behaviorist theory	Learning occurs through stimulus–response reinforcement and repetition; feedback strengthens correct behaviors and procedural memory.	VR provides repeated emergency scenario practice (e.g., decompression, firefighting) with immediate feedback; AR/MR display procedural prompts during drills.	Procedural accuracy; automation of safety routines; reduction of human error.	Skinner (1938); Watson (1913); Gagné (1965); Hays (2006); Auer et al. (2021); Kaplan et al. (2021); Peng et al. (2022)
Cognitivist theory	Learning involves encoding, storing, and retrieving information while managing cognitive load; mental models guide problem solving.	AR/MR embed instructions directly into cabin elements, minimizing cognitive overload; VR translates abstract principles (e.g., pressure loss) into vivid experiences that support memory retention.	Enhanced comprehension; improved knowledge transfer; efficient information processing under pressure.	Bruner (1966); Gagné (1965); ISO (2019); Merchant et al. (2014); Borgen et al. (2021); Gangabissoon et al. (2020); Dymora et al. (2021); Wu and Vu (2022)
Constructivist and experiential learning	Learners construct knowledge through active engagement, reflection, and contextual experience; learning is iterative and self-regulated.	AR fosters interactive, context-based decision-making and collaboration; VR simulates real emergencies following Kolb's (1984) cycle, experience, reflection, conceptualization, experimentation.	Critical thinking; adaptive problem-solving; emotional resilience; deep conceptual understanding.	Piaget (1970); Kolb (1984); Hays (2006); Radianti et al. (2020); Safi and Chung (2021); Bailey et al. (2017)
Social learning theory	Learning occurs through observation, modeling, and interaction within social contexts; collaboration enhances knowledge internalization.	Multi-user AR/VR environments allow pilots and crew to coordinate, observe, and replicate effective behaviors in shared simulations, supporting crew resource management.	Team communication; leadership; shared situational awareness; collective decision-making.	Bandura (1986); Vygotsky and Cole (1978); Moesl et al. (2022); Weelden et al. (2021)

cultures, and training structures, enabling examination of immersive learning perceptions across different organizational contexts within the national aviation sector.

Heterogeneity was sought across key demographic and professional characteristics, including age, gender, educational background, years of experience, current role, and level of familiarity with extended reality technologies. This variation allowed inclusion of both XR-informed and XR-inexperienced perspectives without adopting an experimental or control-group structure, strengthening the interpretive depth of the study while preserving its exploratory orientation.

Eligibility required participants to be currently employed as cabin crew, to voluntarily consent to participation, and to have not received XR-based training during the preceding year. Individuals in purely administrative or managerial roles, or those with prior XR training exposure, were excluded to maintain focus on frontline operational perspectives.

Recruitment proceeded until thematic saturation was reached, defined as the point at which additional interviews yielded no substantially new insights or conceptual categories (Wolfswinkel et al., 2013). This criterion supports the sufficiency and credibility of the dataset for meaningful interpretation.

The sample displayed balanced gender representation, included both early-career and experienced crew members, reflected both airline types, and demonstrated predominantly moderate to high levels of digital literacy.

The participant selection process was documented using a PRISMA-style flow structure to ensure transparency and methodological clarity. This process is summarized in Fig. 1. Detailed demographic and professional characteristics of the sample are presented in Table 2.

3.3. Data collection

Data were collected through a two-stage process combining an open-ended electronic questionnaire and in-depth semi-structured interviews. This sequence enabled an initial exploration of participants' views followed by deeper examination of their experiences with immersive learning technologies in aviation training.

The electronic questionnaire functioned as an exploratory instrument, allowing participants to express preliminary reflections on the use of extended reality technologies in their own words. Questions focused on the perceived value of immersive technologies compared with conventional instruction, addressing areas (e.g., motivation, situational awareness, teamwork, and perceived technical or organizational barriers to adoption) (Auer et al., 2021; Wu and Vu, 2022).

Building on these responses, semi-structured interviews were conducted to capture more detailed experiential accounts. Interviews were carried out both online and face to face, depending on participant availability. Each session lasted between 45 and 60 min. The interview guide followed a flexible structure that ensured consistent coverage of key themes while allowing exploration of emerging issues and clarification of participants' perspectives. All interviews were audio recorded with informed consent to preserve accuracy for transcription and analysis.

Ethical procedures were followed throughout the data collection process. Institutional review board approval was obtained prior to the study, and participants provided digital informed consent. Identifying information was removed from transcripts, and all materials were stored securely in accordance with established qualitative research standards to ensure confidentiality and data protection (Moher et al., 2010).

For transparency, the full set of interview questions is provided in Appendix 1 to demonstrate their alignment with the study's research objectives.

3.4. Systematic literature review and meta-analysis

A systematic literature review was conducted in accordance with

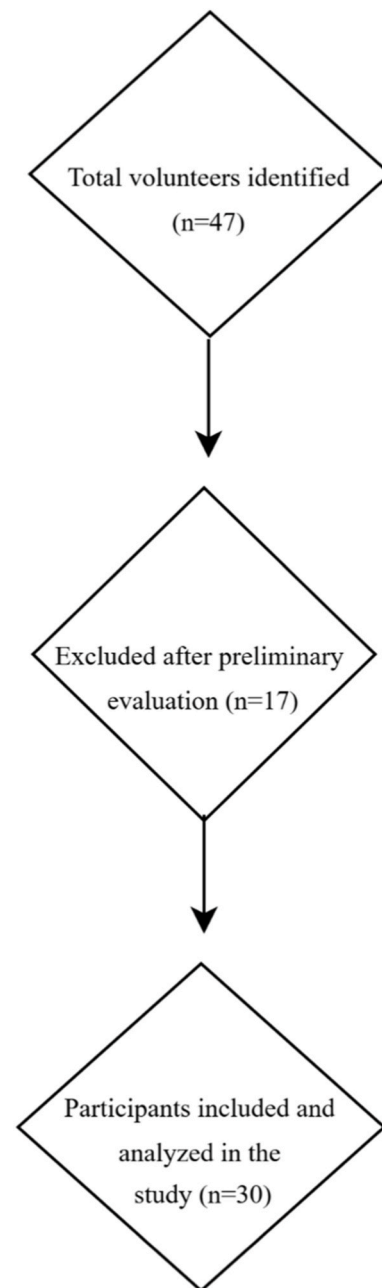


Fig. 1. Participant selection process.

PRISMA guidelines to complement the primary qualitative data. Searches were performed in Scopus, Web of Science, IEEE Xplore, and the ACM Digital Library using Boolean combinations of the keywords “cabin crew training,” “virtual reality,” “augmented reality,” and “mixed reality” (Cipresso et al., 2018; Kaplan et al., 2021).

Explicit inclusion and exclusion criteria were applied to identify empirical studies examining XR-supported aviation or safety training. Methodological quality was assessed using the Critical Appraisal Skills Program (CASP) checklist to ensure analytical rigor (Radianti et al., 2020).

3.5. Validity and reliability

Credibility, transferability, dependability, and confirmability were addressed through multiple procedures. Triangulation with established XR and aviation literature supported the interpretation of emerging

Table 2
Demographic and professional distribution of participants.

Characteristic	Subcategory	n	%
Gender	Female	15	50
	Male	15	50
Age	20–29	10	33
	30–39	11	37
	40+	9	30
Marital status	Married	12	40
	Single	18	60
Education	Associate's degree	3	10
	Bachelor's degree	22	73
	Master's degree	5	17
Airline type	Flag carrier	17	57
	Low-cost	13	43
Position	Cabin crew	17	57
	Cabin chief	6	20
	Purser	5	16
	Trainer	2	7
Experience (Years)	0–1	4	13
	2–4	7	23
	5–9	7	23
	10–19	9	30
	20+	3	10
Flight type	Domestic only	2	7
	Both domestic and international	28	93
Digital literacy	1–2 (Low)	4	13
	3–4 (Medium)	15	50
	5 (High)	11	37
Learning style	Visual	11	37
	Kinesthetic	10	33
	Auditory	5	17
	Reading/writing	4	13

themes (Patton, 1999). An audit trail documented each stage of the research process from transcription through coding and theme development, allowing the analytical process to be reviewed for consistency.

Reflexive journaling was maintained throughout data collection and analysis to monitor researcher influence and maintain transparency (Denzin and Lincoln, 2018). Contextual descriptions of the training environment, participant characteristics, and data collection conditions are provided to support assessment of transferability.

Dependability and confirmability were strengthened through independent coding by two researchers, with discrepancies resolved through discussion and consensus. Member validation was conducted by inviting selected participants to review preliminary interpretations. Identifying details were removed during transcription, and electronic records were stored securely in accordance with qualitative research standards (Moher et al., 2010).

Table 3 presents a summary of the strategies used to ensure validity and reliability, including triangulation, audit trail documentation, reflexive journaling, member checking, independent coding, and rich contextual reporting.

3.6. Data analysis

The qualitative dataset was analyzed using thematic analysis, enabling a systematic yet flexible examination of both explicit and

Table 3
Validity and reliability.

Strategy	Description
Diverse participant group	Diversity in age, gender, education, and experience
Double coding	Independent coding by two researchers, consensus process
Member check	Validation of interview summaries by participants
Detailed reporting	Transparent and traceable presentation of analysis processes
External audit	Openness of the research to external review

underlying meanings within participants' narratives (Braun and Clarke, 2006). The analysis proceeded through iterative stages to ensure depth and methodological rigor.

The process began with repeated readings of all interview transcripts and questionnaire responses to achieve close familiarization with the content and to note initial impressions of recurring ideas and subtle expressions. During the open coding phase, each transcript was examined line by line, and meaningful segments of text were assigned descriptive codes that captured key ideas (e.g., enhanced situational awareness, increased motivation, hardware discomfort, and collaborative problem solving). This phase provided a detailed foundation for identifying the full range of participant perspectives.

The analysis then advanced to axial coding, in which related codes were grouped into broader conceptual categories. This step made it possible to identify higher-level relationships and emerging structures within the data. For example, initial codes were clustered into broader categories (e.g., cognitive benefits, motivational influences, technological barriers, and teamwork related learning outcomes). These categories were subsequently refined and consolidated into a set of overarching themes that explain how immersive technologies shape learning processes, professional reflexes, and engagement among cabin crew members.

To ensure the credibility and dependability of the analysis, two researchers coded the data independently and later compared their results. Any differences were resolved through collaborative discussion until full agreement was reached. Member checking was also conducted by inviting selected participants to review the preliminary themes and confirm that they accurately reflected their experiences and viewpoints. These measures strengthened the analytical rigor of the study and minimized potential researcher bias.

Table 4 presents a synthesis of the thematic analysis, summarizing the main themes, their associated categories, and representative codes that emerged from the data. It serves as a concise visual overview of how the raw qualitative material was structured and interpreted, demonstrating the systematic progression from initial coding to theme development. This iterative and collaborative approach provided an empirically grounded and transparent understanding of how XR technologies affect cabin crew learning, motivation, and professional adaptation.

4. Findings

This section synthesizes evidence from the systematic literature review, meta-analytic findings, and in-depth interviews to examine how immersive technologies shape cabin crew learning and professional readiness.

4.1. Evidence from the systematic review and meta-analytic synthesis

Following full-text evaluation, 87 studies met the inclusion criteria, of which 33 were comparative or meta-analytic. These studies were systematically coded according to training domain, immersive technology modality, and learning outcomes. The quantitative synthesis consistently demonstrated that immersive training environments generate measurable advantages over traditional classroom and simulator-based instruction.

Quantitative synthesis of the reviewed studies indicates that XR-based education has been associated with average learning-performance improvements between 24% and 31% and reductions in procedural error rates between 14% and 19%, as reported in prior comparative and meta-analytic studies, when contrasted with conventional training approaches. These findings indicate that immersive technologies contribute not only to technical skill acquisition but also to heightened engagement, situational awareness, and cognitive preparedness in high-risk operational settings (Kaplan et al., 2021; Merchant et al., 2014).

Table 4
Coding framework for qualitative data analysis.

Theme	Category	Representative codes	Interpretation
1. Cognitive and knowledge outcomes	Declarative knowledge	“Better recall of safety steps,” “Easier to memorize cabin procedures”	XR supports retention of factual information by visualizing abstract concepts (Merchant et al., 2014; Radianti et al., 2020).
	Procedural knowledge	“Hands-on practice,” “Automatic emergency response”	Repetition in VR enhances procedural memory, consistent with behaviorist learning principles (Hays, 2006; Kaplan et al., 2021).
	Situational awareness	“More aware of environment,” “Realistic emergency cues”	Immersive settings heighten awareness of context-specific variables critical in aviation (Auer et al., 2021).
2. Motivation and engagement	Immersion and presence	“Felt like real cabin,” “Total focus”	High immersion leads to stronger engagement and reduced distraction (Slater and Sanchez-Vives, 2016).
	Emotional involvement	“Less boring than classroom,” “More motivated to participate”	Positive emotions foster intrinsic motivation and deeper learning (Zmigrodzka and Kostur-Balcerzak, 2018).
	Confidence building	“Less nervous in real drills,” “Prepared for emergencies”	XR provides safe rehearsal, enhancing self-efficacy (Gangabissoon et al., 2020).
3. Social and collaborative learning	Crew interaction	“Worked as a team,” “Simulated passenger communication”	Multi-user XR replicates teamwork dynamics, aligning with social learning theory (Weelden et al., 2021).
	Peer modeling	“Learned by watching others in VR”	Observational learning supports collaborative skill acquisition (Safi and Chung, 2021).
	Communication skills	“Practiced instructions,” “Clearer commands under stress”	Training emphasizes CRM competencies.
4. Technological and practical constraints	Hardware limitations	“Headset heavy,” “Motion sickness”	Ergonomic issues limit prolonged XR use (Jerald, 2016).
	Access and infrastructure	“Not enough devices,” “Limited classroom integration”	Institutional barriers affect XR adoption (Neretin et al., 2021).
	Fidelity and realism	“Cabin not exactly like real one,” “Limited sensory input”	Perceived gaps between simulation and real-world fidelity (Hays, 2006).
5. Transferability and future application	Knowledge transfer	“Applied training in real flights,” “Remembered VR drills during turbulence”	XR experiences translate into real-world readiness (Wu and Vu, 2022).
	Sustainability	“Could reduce costs,” “Reusable scenarios”	XR seen as a cost-effective long-term training tool (Kaplan et al., 2021).
	Innovation potential	“Next-gen training,” “Future standard for aviation”	Participants view XR as inevitable in modern aviation pedagogy (Safi and Chung, 2021).

A closer examination of the literature reveals complementary strengths across different immersive modalities. MR and AR are particularly effective for real-time, context-based learning by overlaying digital cues and procedural guidance directly onto physical training environments. This supports immediate application of knowledge and strengthens the link between abstract procedures and operational practice. VR, by contrast, provides full immersion and is especially suited to rehearsing complex or high-risk situations (e.g., decompression events and emergency evacuations), allowing repeated practice of rare but critical scenarios without exposing trainees to operational hazards.

This body of evidence strongly supports the integrated use of MR, AR, and VR in cabin crew education to enhance both cognitive and affective learning outcomes. MR and AR provide context-rich guidance during practical exercises, while VR delivers experiential depth and high-fidelity simulation. The aggregate effects identified in the literature provide a benchmark against which the qualitative findings of the present study can be interpreted and understood.

Beyond informing the present research, this synthesis also offers a replicable methodological foundation for examining immersive learning applications in other high-stakes professional domains.

4.2. Interview findings: Effectiveness and comparative evaluation of XR-based training

The qualitative findings show that the integrated use of MR/AR and VR is an effective training approach for cabin crew, primarily due to enhanced realism, repetition, and experiential engagement. Participants emphasized that immersive simulations support both skill acquisition and psychological readiness. Most respondents (92%) reported a strong sense of presence during VR-based emergency scenarios, which was seen as critical for confident performance under pressure. Repeated practice of high-risk situations without real-world consequences was highlighted by 80% of participants as improving procedural fluency and emotional control, while 67% noted better crisis-response reflexes through simulated panic scenarios.

Effectiveness was also evident at team level. Collaborative MR/AR and VR exercises enhanced communication and coordination for 38% of

participants. In addition, 52% stressed the importance of instructor guidance in structuring sessions and providing timely feedback.

The comparative analysis reveals the distinct strengths and limitations of the four primary instructional models used in cabin crew education: traditional classroom-based instruction, MR/AR training, VR training, and the integrated MR/AR and VR approach. Each model contributes differently to the development of professional competence, and their effectiveness varies according to learning objectives and operational needs.

Traditional classroom instruction remains a dependable foundation for conveying theoretical knowledge and procedural standards. However, it provides limited realism and minimal opportunity for teamwork simulation or hands-on crisis rehearsal. These limitations make it insufficient for preparing trainees to manage high-pressure or unpredictable flight situations that require immediate decision-making and coordinated responses.

MR/AR applications enhance practical engagement by projecting digital information and interactive cues directly onto the physical training environment. This allows trainees to visualize procedures in their actual context, strengthening their procedural accuracy and situational awareness. The merging of digital guidance with tangible cabin elements supports experiential learning and helps learners bridge the gap between abstract knowledge and applied skills.

VR training advances this process further by immersing participants in fully simulated environments that replicate complex and rarely encountered emergencies such as decompression events, cabin fires, or large-scale evacuations. This complete immersion enables repeated rehearsal of critical actions within a safe, controlled setting, promoting both technical mastery and emotional resilience.

The integrated MR/AR and VR model demonstrates the most comprehensive benefits. It achieves the highest effectiveness ratings across nearly all evaluated criteria, including realism, learner motivation, procedural precision, flexibility, and crisis management. Although it requires higher initial investment in equipment, software, and instructor preparation, its long-term advantages in knowledge retention, repeatability, and overall cost efficiency make it a sustainable and forward-looking approach to aviation training.

Table 5 provides a detailed comparison of performance indicators across these four training models, summarizing their relative effectiveness in realism, practical application, learner engagement, flexibility, and safety simulation.

Synthesizing the qualitative findings with evidence from the wider literature reveals that crisis management, learner motivation, and long-term knowledge retention are the most prominent benefits of integrating XR technologies into cabin crew training. The interview data show that 88% of participants reported significant improvement in their ability to respond to crisis situations, while 75% emphasized increased motivation and a stronger willingness to learn.

At the same time, several implementation challenges emerged. Nearly half of the respondents identified the need for enhanced infrastructure and access to modern equipment. In addition, 52% stressed the importance of well-prepared trainers who can effectively facilitate immersive learning sessions. More than one third expressed concern about cost-related issues and the long-term sustainability of XR adoption. These concerns align closely with international research, which consistently finds that successful implementation of immersive learning technologies requires more than investment in hardware. It depends equally on continuous instructor development, robust digital infrastructure, and sustained organizational support for change management.

The combined insights from participants and the supporting academic literature are summarized in Table 6, which links each key thematic area with its corresponding level of participant support, the strength of evidence reported in prior studies, and the related implementation needs. This integrated evaluation provides a clear framework for identifying priority areas in aviation education, particularly in enhancing crisis management modules, advancing trainer competency, and designing sustainable infrastructure plans to ensure the long-term effectiveness of XR-based training systems.

5. Discussion and implications

5.1. Theoretical contributions

Building on the integrated findings of the study, the results indicate that XR based training contributes to procedural execution, crisis management capability, learner motivation, and long-term knowledge retention. The convergence of qualitative insights and prior empirical evidence suggests that immersive learning environments support the translation of abstract safety principles into operationally meaningful competence, particularly in high stakes aviation contexts.

This study advances theory in aviation education by positioning XR as a unified pedagogical environment in which multiple learning processes operate simultaneously within a single instructional setting.

Table 5
Comparison of traditional and technology-based training approaches.

Criterion	Traditional method	MR/AR applications	VR applications	Integrated (MR/AR + VR)
Theoretical transfer	+++	++	++	++
Practical application	+	++	+++	+++
Realism	+	++	+++	+++
Teamwork	+	++	++	+++
Motivation	+	++	++	+++
Flexibility	+	++	++	+++
Error/crisis experience	-	++	+++	+++
Equipment requirement	+	++	+++	+++
Cost	++	++	++	+

Note: +++ = Very high, ++ = High, + = Medium, - = Low.

Table 6
General summary of thematic findings and overlap with the literature.

Thematic area	Participant support (%)	Literature support	Implementation need
Crisis management and reflex	88	Strong	Very high
Team coordination	38	Moderate	Moderate
Motivation and desire to learn	75	Strong	High
Technical infrastructure/equipment	46	Strong	High
Trainer/expert competence	52	Strong	Very high
Feedback and assessment	34	Moderate	Moderate
Individualization	30	Moderate	Moderate
Cost and sustainability	37	Strong	High

Rather than relying on a single explanatory lens, the study shows that XR supports learning through a coordinated interplay of reinforcement, cognitive structuring, experiential engagement, and socially situated practice. Immersive training enables learners to interpret complex procedures, rehearse them with confidence, and remain engaged in demanding situations where attention, judgment, and coordination must be sustained.

Prior research on immersive education and training shows that virtual environments can strengthen learning when repetition, feedback, and task realism are aligned with instructional design, while also acknowledging the contextual factors that shape their effectiveness (Jensen and Konradsen, 2018). Related work emphasizes that immersive learning is influenced not only by cognitive processing but also by the experiential and affective qualities of the environment, which can intensify engagement and support deeper learning through realistic exposure (Makransky and Lilleholt, 2018). These perspectives support the view that XR functions as a learning environment in which attention, motivation, and procedural learning are jointly shaped through design and facilitation.

From this standpoint, improvements reported across immersive learning studies can be understood as outcomes of how XR environments structure practice, feedback, and experiential realism rather than as simple technological effects. This interpretation aligns with the view that effective professional learning depends on both cognitive assimilation and the gradual automation of procedures through reinforced practice (Hays, 2006; Mayer, 2011; Skinner, 1938; Watson, 1913).

The study also extends educational theory by showing how XR reduces the separation between knowing and doing in safety critical training. Within immersive settings, learners construct meaning through active problem solving, reflection, and guided collaboration, linking cognitive and experiential learning processes. MR and AR overlays reduce extraneous cognitive load by embedding procedural cues directly into the environment, while VR simulations strengthen schema formation and support memory consolidation and retrieval under complex conditions (Pang and Cai, 2023; Sweller, 1988). Participants' accounts of heightened confidence, improved emotional control, and stronger teamwork indicate that XR fosters both self-regulated and socially mediated learning, consistent with constructivist and social cognitive traditions that emphasize the interdependence of individual understanding and collective performance (Kolb, 1984; Vygotsky and Cole, 1978). In line with aviation training research, collaborative XR features strengthen crew resource management through peer modeling, shared situational awareness, and guided interaction (Moesl et al., 2022; Weelden et al., 2021).

This study extends the theoretical foundations of instructional design for organizations operating under conditions of high reliability through the integration of these complementary mechanisms. It demonstrates that immersive environments can support the simultaneous

development of procedural memory, conceptual understanding, and social coordination, thereby connecting behavioral, cognitive, experiential, and social dimensions of learning that are often treated separately in the literature. In doing so, the research reframes the role of technology in education from a delivery tool to a catalyst for systemic learning transformation.

This theoretical synthesis enriches both aviation management and educational science by showing that XR enabled instruction reflects a multi layered model of learning in which reinforcement, cognition, reflection, and collaboration converge. This integration positions XR as a pedagogically coherent and empirically supported approach for enhancing safety, adaptability, and professional competence in complex operational settings (Salas et al., 2012; Tichon and Burgess Limerick, 2011).

5.2. Practical implications

The patterns identified in this study suggest that improvements in procedural confidence, crisis readiness, and teamwork developed through immersive training can translate into observable operational indicators over time (e.g., response time, procedural accuracy, and crew coordination during recurrent evaluations). These effects, however, do not arise from technology alone. They depend strongly on organizational readiness, instructional competence, and sustained institutional commitment.

For airline management, the findings indicate that immersive technologies should be embedded within corporate training strategy rather than introduced as optional or experimental tools. Integrating VR and AR modules alongside classroom instruction and simulator sessions can strengthen knowledge consistency, procedural reliability, and trainee engagement while improving the efficiency of training delivery. Investment priorities should therefore extend beyond equipment acquisition to include high-fidelity software, ergonomically suitable hardware, and training environments that reduce motion discomfort and cognitive fatigue. Continuous instructor development is central to this process. Certification and recurrent preparation in immersive pedagogy ensure that technological resources are translated into effective learning practice.

For aviation training institutions, curriculum design requires adjustment to incorporate structured immersive components such as VR-based emergency drills, AR-supported safety procedures, and MR-enabled communication scenarios. These modules should be supported by reflective debriefing, adaptive crisis simulations, and collaborative exercises that promote critical thinking and coordinated decision making. Assessment frameworks also require revision. Performance data generated within immersive environments should be formally integrated into competency evaluation and accreditation standards, including those aligned with the European Union Aviation Safety Agency and the International Organization for Standardization (ISO 9241-210). Attention to accessibility is equally important. Supporting trainees with different levels of digital literacy through adaptive interfaces and guidance systems can improve inclusiveness and training effectiveness.

From a regulatory perspective, aviation authorities including the European Union Aviation Safety Agency (EASA), the International Air Transport Association (IATA), and the International Civil Aviation Organization (ICAO) can play a decisive role by establishing harmonized guidance for immersive training implementation. Such guidance should define minimum fidelity requirements, usability benchmarks, and certification principles that ensure consistency across institutions. Because immersive systems often rely on biometric tracking of eye movements, gestures, and spatial data, regulatory frameworks should also emphasize privacy protection and ethical data governance in line with standards such as the X Reality Safety Initiative Privacy Framework.

5.3. Limitations and future research directions

Although the study demonstrates the substantial potential of immersive technologies for aviation training, several methodological and practical limitations should be acknowledged. Participants reported challenges related to hardware ergonomics, motion discomfort, limited equipment access, and variations in simulation fidelity, all of which may constrain large-scale implementation. In addition, the phenomenological design based on purposive sampling of Turkish cabin crew provided rich, contextually grounded insights but does not allow statistical generalization across airlines, operational settings, or cultural contexts. These factors should be considered when interpreting the findings.

The study also relies on perceptual evaluations of immersive training rather than direct measurement of post-training operational performance. Future research would benefit from integrating objective performance indicators collected during recurrent training and operational assessments to examine how immersive learning translates into measurable professional outcomes over time.

Longitudinal investigations are particularly needed to examine the durability and transferability of immersive learning to real flight operations, assessing both immediate skill acquisition and long-term retention. Comparative studies may further clarify the relative effectiveness of different modalities, including fully immersive environments for crisis simulation, context-embedded guidance systems for procedural practice, and hybrid approaches that combine these functions.

Cross-cultural and institutional research is also important to understand how regulatory frameworks, organizational cultures, and workforce characteristics influence the adoption and effectiveness of immersive training systems across aviation contexts. Such studies would help determine how immersive learning can be adapted to different operational environments while maintaining training consistency and safety standards.

Further investigation is required into the psychological and physiological implications of prolonged immersion, including eye strain, cognitive fatigue, and motion discomfort. Addressing these issues is essential for developing sustainable training strategies that balance realism with learner well-being.

These methodological, technological, organizational, and human considerations converge into a set of clear research priorities. Table 7 synthesizes these priorities by mapping the key limitation areas identified in this study to specific avenues for future empirical investigation, providing a coherent agenda for advancing understanding of how immersive learning environments contribute to professional competence and aviation safety.

6. Conclusion

This study shows that immersive XR environments offer meaningful pedagogical advantages for cabin crew training by strengthening procedural memory, situational awareness, motivation, and coordinated teamwork beyond what conventional classroom and simulator-based methods can provide. Rather than serving as a technological supplement, XR emerges as a coherent learning environment that integrates behavioral practice, cognitive processing, experiential engagement, and collaborative interaction within realistic and repeatable scenarios.

At the same time, the findings indicate that effective implementation requires attention to practical constraints, including hardware ergonomics, motion discomfort, device accessibility, and the need for reliable digital infrastructure capable of sustaining high-fidelity simulation. These considerations highlight that successful integration depends not only on technological capability but also on instructor preparedness, institutional planning, and regulatory alignment.

When supported by sustained investment, organizational commitment, and continued research into learning durability and contextual adaptation, immersive technologies hold strong potential to reshape aviation training practices. In this respect, XR can contribute to the

Table 7
Practical recommendations and research priorities for sustainable XR integration in cabin crew training.

Focus area	Actionable recommendation (Practice/policy)	Primary stakeholder(s)	Future research focus	Priority
Crisis and emergency preparedness	Integrate XR-based emergency and evacuation modules as compulsory elements of cabin crew curricula.	Airlines, aviation academies, civil aviation authorities	Examine long-term transfer of XR-acquired crisis-management skills to real-flight contexts and evaluate performance retention over time.	High
Instructor competence and development	Provide continuous professional training for instructors and technical staff to sustain pedagogical and technical proficiency in XR systems.	Training institutions, airlines	Investigate the effect of instructor expertise and facilitation style on learning engagement and knowledge retention.	High
Curriculum design and hybrid integration	Implement a phased hybrid learning model combining traditional instruction with immersive XR modules to maintain curriculum balance and foster innovation.	Academic boards, training departments	Compare the effectiveness of hybrid versus fully immersive curricula across different aviation contexts.	Medium
Infrastructure and equipment investment	Establish strategic plans for hardware renewal, maintenance, and scalability to support sustainable XR integration.	Airlines, regulators, technology providers	Evaluate cost-benefit ratios, accessibility, and scalability of various XR platforms in large training programs.	High
Performance monitoring and feedback	Develop digital analytics systems that track learner engagement, accuracy, and procedural adherence across XR environments.	Airlines, training academies	Explore AI-driven adaptive feedback mechanisms and biometric monitoring to personalize XR learning experiences.	Medium
Learner support and digital inclusion	Offer learner-centered guidance and modular training to accommodate diverse digital literacy levels and reduce technology-related anxiety.	Trainers, HR divisions	Assess how demographic, cultural, and cognitive differences influence the adoption and learning outcomes of XR tools.	Medium
Content maintenance and updating	Introduce systematic content-review cycles to ensure XR modules reflect current operational standards and safety regulations.	Regulatory bodies, training developers	Study the influence of content update frequency on learner motivation and knowledge retention.	High

development of cabin crew competence suited to both routine service conditions and complex, high-pressure operational situations that characterize contemporary civil aviation.

CRedit authorship contribution statement

Nilgun Yildirim: Writing – original draft, Resources, Investigation, Conceptualization. **Ekrem Tatoglu:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Halit Keskin:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation. **Emel Esen:** Writing – review & editing, Writing – original draft,

Visualization, Supervision, Resources, Methodology.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors edited the manuscript using Generative AI tools. After using these tools, they reviewed and edited the content as needed and took full responsibility for the content of the published article.

Conflict of interest

The authors declare no conflicts of interest.

Appendix 1. Interview questions

Section	Questions
1. Attitudes and perceptions towards technology	<ol style="list-style-type: none"> 1. You mentioned that you have never experienced virtual reality (VR) technology before. What do you generally know about this technology? 2. In your opinion, what advantages or disadvantages might arise from using VR technology in educational settings? 3. Have you ever seen such technologies used in education before? (e.g., video, presentations, social media, etc.) 4. Do you have any positive or negative biases or concerns regarding VR?
2. Professional readiness and educational needs	<ol style="list-style-type: none"> 1. To what extent has the cabin crew training you received prepared you for real flight conditions? 2. What aspects of your training did you find challenging or insufficient? 3. Do you think virtual reality technology could be useful in improving these areas? Why?
3. Adaptability to technology and learning style compatibility	<ol style="list-style-type: none"> 1. Among visual, auditory, or experiential (kinesthetic) methods, which is more effective for you in training? 2. Do you think you would feel comfortable in a technologically enhanced training environment like VR? 3. What aspects do you think might make it difficult for you to adapt to this technology?
4. Intention to participate and expectations	<ol style="list-style-type: none"> 1. If you were offered a VR-based in-cabin emergency scenario, would you like to experience it? Why? 2. If you participated in such training, how do you think it would contribute to your professional skills? 3. Do you think training delivered via VR could be more effective than traditional classroom training?
5. Institutional integration and mandates	<ol style="list-style-type: none"> 1. Do you think technologies like VR should be made mandatory in cabin crew training? 2. If such innovative training models were implemented for all personnel, what kind of challenges might arise? 3. If your training institution or airline offered a VR-based module, what factors would influence your decision to participate?
6. Suggestions for development and dissemination	<ol style="list-style-type: none"> 1. In your opinion, what features should a VR-based training system have to be effective? 2. What topics would you prioritize to be included in the training content? 3. What do you think about how instructors, content, or technical infrastructure should be designed to ensure training success?

Data availability

Data will be made available on request.

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