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Virtual Reality and Augmented Reality in Aviation Education and Pilot Training: A Systematic Review

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ABSTRACT: This systematic review investigates how Virtual Reality (VR) and Augmented Reality (AR) technologies transform aviation education and pilot training programs. The study used the PRISMA 2020 framework to synthesize empirical data, review articles and foundational literature which authors published between 2020 and 2026 in Scopus and IEEE Xplore, ScienceDirect, SpringerLink, Web of Science and Google Scholar databases. Eight core studies and additional foundational references were analyzed to evaluate the effectiveness of immersive technologies in improving pilot performance, procedural learning, situational awareness, learner engagement, accessibility, and training efficiency. The study results show that virtual reality and augmented reality systems improve knowledge retention, help users develop procedural skills, and increase student motivation, while these systems provide affordable solutions that can be implemented on a large scale to replace conventional flight simulators. Current studies demonstrate that aviation training environments now use artificial intelligence combined with adaptive learning systems and biometric tracking and mixed reality technologies. The aviation education system needs to address three main challenges which include cybersickness issues, the high expenses of equipment, the lack of instructor preparedness and the need to evaluate how training sticks with students throughout their entire learning process.

KEYWORDS: Artificial Intelligence, Augmented Reality, Aviation Education, Immersive Learning, Pilot Training, Virtual Reality

INTRODUCTION

Immersive learning technology has changed the way aviation training is delivered through the use of Virtual Reality (VR) and Augmented Reality (AR). Such technologies provide safe, cost-effective, and immersive learning environments that help pilots and aviation students develop procedural accuracy, situational awareness, and decision-making skills traditionally acquired through aircraft operations or expensive simulator training (Cross et al., 2023; Ross & Gilbey, 2023). Immersive learning systems have been adopted by the education sector during the last ten years to be able to evaluate the Extended Reality (XR) systems. The XR systems act as educational tools, replacing conventional training practices in the field of aviation, but also supplementing them as stated by Jevčák et al. 2024. and Ziakkas et al. 2023.

Recent developments show that VR systems now provide better support for versatile training programs which can be tailored to individual needs of aviation pilots. According to Weelden et al. (2021), by applying neurotechnology with VR, VR trainers can enjoy an important benefit of observing how trainees perform in VR simulation by analyzing their cognitive and physical reactions. The trainers then can give instant feedback and modify the whole process of training, depending on the experience of each participant. Likewise, Fussell & Truong (2022, 2023) indicate that students are more likely to actively participate in VR learning sessions when they find VR technology practical, convenient, and fun to use. Moreover, Jevčák et al. (2023) state that VR technologies will be successfully used in aviation training programs, if organizations possess good digital facilities, developed curriculum, and a competent trainer to help their students learn better.

In any case, AR continues evolving as an equally viable partner for VR applications. The paper by Moesl et al. (2021) indicated that an appropriate research agenda is exploring the use of AR for pilot training for beginners, which implied questions related to teacher training, user interface creation, and learning effects verification. The more recent literature highlights the importance of visual consistency (non-separability of the virtual world from reality) to relieve cognitive overload and provide realistic training (Gorbunov & Li, 2023). Therefore, all inventions are a result of the constant development of immersive learning solutions toward more realistic and humane ones.

Despite the rapid growth of VR and AR technologies in terms of training aviation specialists, inconsistencies have been identified in previous studies as regards effectiveness of training, application context, phases of training and criteria for assessing the learners' performance. Moreover, little is known about long-term transfer of skills acquired during training, instructors' ability to conduct training using new technology, institution's capacity to introduce this innovation, and applications of emerging technology in aviation training. Therefore, this systematic literature review aims to synthesize empirical and foundational literature on the use of VR and AR technologies in aviation education and pilot training. In particular, this study will explore the influence of the technologies of VR and AR on such aspects as learning outcomes, learner experience, accessibility, cost-effectiveness, cognitive and human factors, as well as implementation issues while simultaneously highlighting new trends, research gaps, and possible avenues in this area of study.

LITERATURE REVIEW

Recent developments in immersive aviation training have increasingly emphasized the integration of Artificial Intelligence (AI), adaptive learning systems, physiological monitoring, and mixed reality environments into pilot education. The previous studies focused on testing the effectiveness of VR/AR as a replacement or supplementary tool for simulators while recent results show that intelligent training applications which use data to customize their cognitive training methods are essential for effective training.

Shaker & Al-Alawi (2023) performed a systematic analysis concerning the implementation of big data and AI in the training of pilots and reported that with the help of AI, there can be notable improvements in terms of training customization, prediction, and decision making. Specifically, Shaker and Al-Alawi (2023) noted that machine learning could play an important role in helping to analyze pilot performance, find any deficiencies, and create effective ways to respond to such problems. In this regard, the above discussion is consistent with the research carried out by Guevarra et al. (2023), where the use of AI-based pilot training systems will help learn faster and spend less time on training.

Another important research area investigates how cognitive load in immersive training environments should be managed. The study by Lämsä et al., (2023) shows that authentic VR flight training environments can use multiple behavioral and physiological indicators to assess cognitive load which includes heart rate variability and environmental interactions. The results presented by the authors prove the claim that immersive training systems have the potential not only to simulate procedures but also to monitor the states of learners in real time. Similarly, the research carried out by Hebbar et al., (2023) had been carried out to find out the cognitive workload of pilots during their virtual flights through the help of eye tracking technology. The results obtained during this investigation showed that various physiological cues may be used to assess the workload and situational stress of pilots.

The development of adaptive virtual reality systems is also gaining relevance in the sphere of aviation training. According to Reyes et al., an adaptive VR system was developed for the purposes of pilot training based on VR technology. The study demonstrated the importance of using the proposed adaptive virtual reality system as the possibility for adaptation and adjustment of training sessions based on users' performance and cognitive load.

The research on AR and mixed reality systems has expanded the use of immersive learning for aviation training purposes. According to Li and his colleagues (2022), the research they conducted aimed at examining the impact of AR-based interactive designing on pilots concerning the assessment of workload and maintenance of situational awareness. They noted that the design of an AR interface could minimize cognitive load and enhance situational awareness among pilots. The study is relevant in situations with heavy workload among pilots where the interface design plays an important role in determining their effectiveness. Liedtke et al. (2023) went ahead to extend this concept by creating a mixed reality system aimed at developing holographic cockpit instrumentation. This indicates the potential of immersive interface designs in training future pilots regarding cockpit avionics and operations. Immersive visualization technology in pilot courses became a matter of concern, with a view to increasing adaptability, as mentioned by Livatino et al., (2022).

Moreover, the literature is also exploring the area of training transfer and fidelity of the simulators. According to the results obtained by Somerville et al. (2026), the use of virtual reality for personal computer aviation training devices (PCATDs) helped improve the training transfer in case of teaching students flying an airplane using instruments. The research proves the existing theory that virtual reality may help achieve comparable results in terms of learning as traditional simulators but at a lower cost. Additionally, Myers et al. (n.d.) highlighted that the fidelity of simulators was not a crucial aspect when considering effective training transfer.

VR is also finding growing interest in the context of Crew Resource Management (CRM), and collaboration training systems. In addition, as noted by Duruaku et al. (2023), VR was adopted as an additional tool for CRM training based on scenarios and exhibited its potential to improve communication and decision-making skills among crews. Therefore, it is possible to adopt VR technology in the training process both to learn processes and technical skills and interpersonal ones.

While immersive technology is becoming increasingly beneficial for training, there are still some difficulties involved. In this regard, Mittelstaedt et al., 2024 conducted a study to examine the issue of cybersickness of individuals making use of the VR devices while carrying out simulations of aircraft turbulence. It has been identified by these scholars that some of the variables involved in motion dynamics and virtual reality have played an important part in producing discomfort among users.

Collectively, these newer studies extend the existing literature by demonstrating that immersive aviation education is evolving from static simulation-based instruction toward intelligent, adaptive, and physiologically responsive learning ecosystems. The combination of artificial intelligence, cognitive monitoring, adaptive feedback technology, and mixed reality systems implies that future training for pilots can be more personalized, data-oriented, and practical. Nevertheless, further examination of the literature reveals that there are still some challenges regarding readiness of the instructors, transferability of training, regulation issues, high costs of hardware, and human factors that need to be addressed. Therefore, future studies need to focus on validation tests, standardization, and institutional integration.

METHODOLOGY

A. Research Design

This study used a systematic literature review approach guided by the PRISMA 2020 framework (Page et al., 2021) to examine the role of Virtual Reality (VR), Augmented Reality (AR), and other immersive technologies in aviation education and pilot training. The review included 8 core studies identified through systematic screening and additional foundational and theoretical references related to artificial intelligence (AI), cognitive load, adaptive learning systems, simulator fidelity, and immersive training environments.

Table 1. Research Design Overview

Component	Description
Research Method	Systematic Literature Review
Review Framework	PRISMA 2020
Main Focus	VR, AR, XR, AI, and immersive technologies in pilot training
Sources Included	Empirical studies and foundational/theoretical references
Language	English
Publication Years	Primarily 2020–2026

B. Literature Search Strategy

Relevant studies regarding immersive air training technology were identified through database searching for hits through relevant keywords.

Table 2. Databases and Search Keywords

Category	Details
Databases Used	Scopus, IEEE Xplore, ScienceDirect, SpringerLink, Google Scholar, Web of Science
Search Keywords	"virtual reality," "augmented reality," "mixed reality," "extended reality," "pilot training," "aviation education," "flight simulation," "AI-assisted training"
Types of Sources	Journal articles, conference papers, systematic reviews, and theoretical studies

Searches for relevant articles led to a selection of 61 articles related to immersive technology in aviation training. After screening and selection process, eight articles containing qualitative information were selected for analysis. Other reference materials have been used to back up discussions on theory and technology in immersive aviation training. The total number of articles that have been referred in the paper is 27.

C. Inclusion and Exclusion Criteria

Studies were screened to ensure relevance to aviation education and immersive learning technologies.

Table 3. Inclusion and Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
Studies related to aviation education or pilot training	Studies unrelated to aviation
Use of VR, AR, XR, MR, or AI-assisted systems	Studies without immersive technology applications
Empirical or theoretical contribution	Opinion papers or editorials
Reported educational or training outcomes	Purely technical studies without educational focus
Peer-reviewed or reputable conference papers	Non-English publications

D. Data Extraction and Analysis

Information from the selected studies was extracted and analyzed to identify common themes and findings related to immersive aviation training.

Table 4. Data Extraction Categories

Category	Extracted Information
Technology Used	VR, AR, XR, AI systems
Training Context	Academic, civilian, military aviation
Participants	Student pilots, instructors, professional pilots
Learning Outcomes	Knowledge retention, engagement, procedural skills, situational awareness
Human Factors	Cognitive load, workload, simulator sickness
Implementation Factors	Cost, accessibility, scalability, instructor readiness

The studies were synthesized using thematic analysis to identify trends, benefits, challenges, and future directions in immersive aviation education.

E. PRISMA Flow Diagram

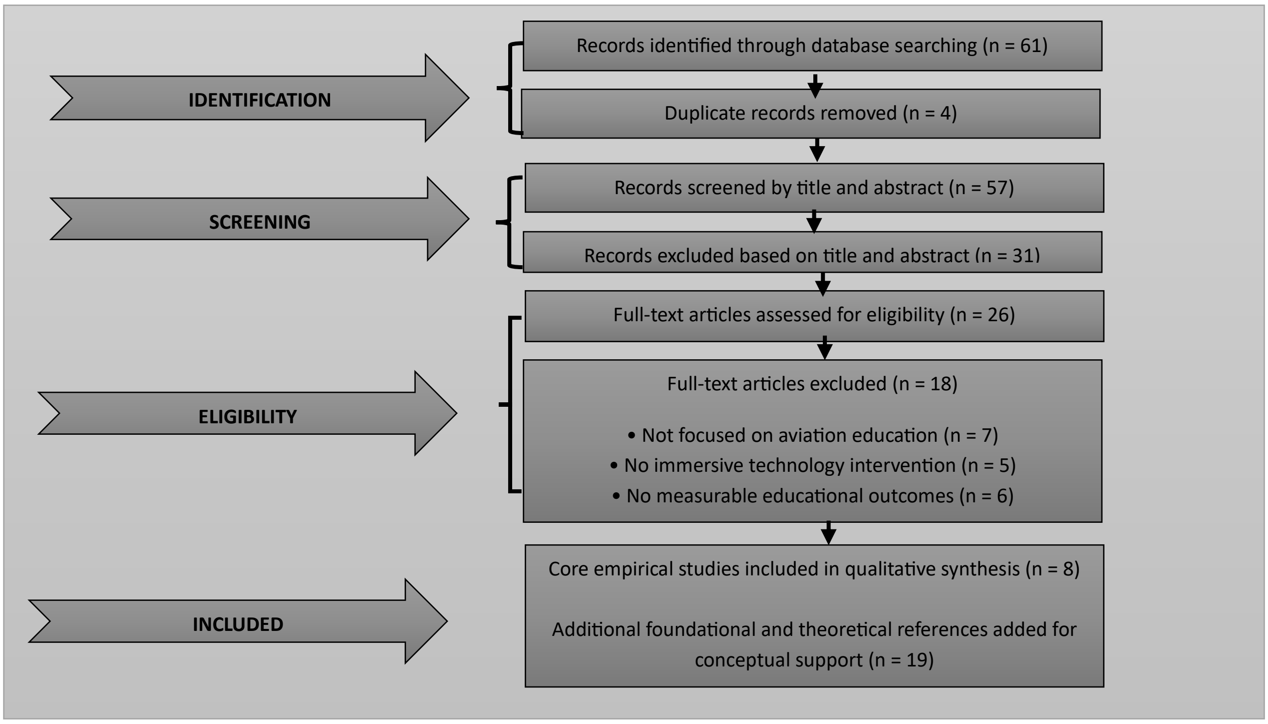

Figure 1. PRISMA Flow Diagram of Study Selection Process

RESULTS AND SYNTHESIS OF THE LITERATURE

The next section will describe the outcomes of the systematic literature review, synthesizing evidence from the eight central studies.

A. Summary of Included Studies

Table 5. Overview of Included Studies

STUDY	STUDY FOCUS	TECHNOLOGY TYPE	TRAINING CONTEXT	STUDY DESIGN
Guthridge and Clinton-Lisell, 2023	Efficacy of Virtual Reality for instrument pilot training	Virtual Reality (HTC Vive Pro, force-feedback yoke, X-Plane 11)	Academic/university; beginning-level instrument pilots; instrument training course	Mixed-methods empirical; quasi-experimental; sample size = 120
Thomas et al., 2023	Virtual Reality for aviation visual/vestibular illusion training	Virtual Reality (Valve Index, Force Dynamics 401cr Motion Simulator, VRAIT software)	Academic/university; mixed-level pilots; visual/vestibular illusion training	Empirical; pre/post design; sample size = 215
Ziakkas et al., 2023	Virtual Reality/metaverse for practical aviation education	Virtual Reality (hardware/software not specified)	Academic/university; undergraduate aviation; flight and maintenance	Empirical; Virtual Reality vs. video-based; no mention found for sample size
Hight et al., 2022	Virtual Reality vs. Two-Dimensional simulation for ab initio pilot training	Virtual Reality (Head-Mounted Display, Virtual Reality lab; software unspecified)	Academic/university; ab initio civilian pilots; pre-solo phase	Quasi-experimental; Two-Dimensional vs. Virtual Reality; sample size = 17
Ross and Gilbey, 2023	Extended Reality as adjunct to traditional flight training	Extended Reality (Virtual Reality, Mixed Reality; hardware/software not specified)	Civilian (61%) and military (39%) flight training; student and qualified pilots	Scoping review; 18 studies (2018–2021)
Dymora et al., 2021	Virtual Reality for pre-flight inspection training	Virtual Reality (HTC Vive goggles, virtual gloves, Blender 2.80)	Academic/university; student pilots; pre-start procedure	Empirical; sample size = 17

Cross et al., 2022	Extended Reality in flight simulators: literature review	Extended Reality (Virtual Reality, Augmented Reality; hardware/software not specified)	Academic, commercial, military; pilot training	Systematic quantitative literature review; 39 papers
Schaffernak et al., 2020	Augmented Reality application areas in pilot education	Augmented Reality (smartphones, tablets, HoloLens)	Commercial aviation; student and experienced pilots, instructors; Private Pilot License (Aeroplane), Type Rating	Empirical survey; sample size = 60

Table 5 provides a summary of the studies analyzed with regard to the technology used, training context or environment and the study design.

Technology Type: Five studies used fully immersive technology in the form of Virtual Reality (VR). Two studies used Immersive Technology in the form of Extended Reality (XR), which might involve use of VR, Augmented Reality (AR) or Mixed Reality.

Training Context: Six of the studies carried out were in an educational/university environment, while two were set in a civilian pilot training environment. Two of the studies also considered applications in a military training environment, while two considered applications in a commercial aviation environment. The participants consisted of student pilots (n=3), qualified/experienced pilots (n=2), and instructors (n=1). In the field of training levels, there were three studies with ab initio pilots.

Study Design: Out of the eight studies, six reported using empirical designs, including quasi-experimental, pre/post, survey, and comparative designs (i.e., comparison of VR to video-based instruction and comparison of Two-Dimensional to VR learning). Two were classified as quasi-experimental, and one utilized a pre/post design, one was a survey, and one was a comparative study. The other two studies were literature reviews, consisting of one scoping review and one systematic quantitative review.

Sample Size (only for empirical studies): Sample Size (will be given for empirical studies): The samples in the 5 empirical studies reported were 120, 215, 17, 17 and 60 subjects. One of the empirical studies did not indicate its sample size. The two literature reviews did not have sample sizes reported because they were literature reviews.

B. Learning Outcomes and Performance Effects

Table 6. Comparison of Learning Effects Across Studies

Study	Outcome Measure	Virtual Reality Results	Augmented Reality Results	Comparison to Traditional Methods
Guthridge and Clinton-Lisell, 2023	Altitude/cross-track accuracy, performance scores	Significant improvement; Virtual Reality = Personal Computer-based; both greater than control	No mention found	Virtual Reality and Personal Computer-based equally effective; both outperform no training
Thomas et al., 2023	Knowledge, self-efficacy (pre/post)	Significant improvement (knowledge: +15 points; self-efficacy: +2.8 points)	No mention found	Virtual Reality training reported as cost-effective, accessible, and without reported risks in the study; no direct traditional comparator
Ziakkas et al., 2023	Knowledge retention, attendance	Virtual Reality group significantly better on knowledge tests (as reported in the study; sample size not mentioned)	No mention found	Virtual Reality greater than video-based training; improved engagement and cognition reported
Hight et al., 2022	Academic performance, engagement	No significant difference in final scores; high engagement	No mention found	Virtual Reality = Two-Dimensional simulation; both preferred over other materials

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Ross and Gilbey, 2023	Learning experience, skill acquisition	Positive learning experiences in 13 studies; Extended Reality as effective as legacy in 5	No mention found	Extended Reality as effective as traditional in some studies; cost/time savings reported
Dymora et al., 2021	Correct answers, skill transfer	90% correct; 21–32.7% higher than traditional; 11/17 could transfer to real aircraft	No mention found	Virtual Reality greater than traditional; some discomfort reported
Cross et al., 2022	Cognitive learning outcomes	Promising cognitive outcomes	No mention found	Supplement classroom/procedure training; skills transfer not evaluated
Schaffernak et al., 2020	Engagement, preferences	No mention found	Engagement via gamification; Augmented Reality preferred for navigation, inspection, theory	Not explicitly compared; Augmented Reality seen as supplement/enhancement

Table 6 lists the main results and comparative findings on studies in aviation education which deal with Virtual Reality (VR) and Augmented Reality (AR).

Results with Virtual Reality: Four of the studies had greatly increased performance, performance accuracy or learning of knowledge, while in one study there was no significant difference between the VR and conventional teaching. Two studies reported positive learning experiences and cognitive outcomes, such as enhanced self-efficacy and situational awareness.

Comparison to Other or Conventional Methods: Three studies indicated VR as better than conventional, video-based, or no-training conditions, whereas three indicated VR to be as effective as other simulation-based or two-dimensional systems. Two articles indicated that VR/AR was used as an improvement for classroom-based training programs by increasing engagement and interest. Time-saving and cost-effective nature of using VR/AR in training programs were mentioned in one article, and one other mentioned that there were minimal symptoms of simulator sickness in participants.

Augmented Reality Findings: AR-specific results were found in a single study, which discovered that AR increased engagement and was used preferentially for navigation, inspection, and theoretical learning via gamified interfaces. The other studies either had a primary focus on VR or did not yield clear AR results.

C. Cost and Accessibility Advantages

Several studies showed VR and XR and other technology as a cost effective, scalable substitute for the traditional simulators, since they may substantially diminish the training time required, the space and physical infrastructure involved, as well as the environmental impact. Although high initial hardware costs were raised as a drawback, the general evidence was centered on cost-effectiveness and increased accessibility.

D. User Experience and Acceptance

Student satisfaction and involvement were always high, with users characterizing VR and AR as good and encouraging tools for learning. Some research studies pointed out the discomfort with the simulator as well as ergonomic limitations, but they seemed to be insignificant in nature. One study showed that the use of gamification among genders differed as female users preferred feedback-oriented games while male users liked narrative-oriented games.

E. Overall Impact of VR and AR in Aviation Training

Overall, these studies indicate that VR and AR improve knowledge retention, skills and motivation in pilot training. In many cases, VR is equal to or better than traditional teaching methods and comes with the benefits in cost effectiveness as well as accessibility. While technical and ergonomic challenges persist, overall user acceptance remains strong.

Thematic Analysis

Table 7 demonstrates how VR and AR are utilized in training across all phases, the main obstacles and contributors to their use, and the possibilities to improve engagement and accessibility in aviation education.

Table 7. Thematic Analysis of Included Studies

Theme	Description	Representative Insights from Included Studies
Applications Across Training Phases	VR was primarily used for flight simulation, maneuver, and procedural skill training in ab initio and undergraduate contexts. The use of AR technology was for navigation, theoretical training, and pre-flight training, which created more interest in the area. Both technologies can be considered an alternative to traditional simulators.	Dymora et al. (2021); Thomas et al. (2023); Schaffernak et al. (2020); Cross et al. (2022)
Implementation Barriers and Facilitators	Some challenges were the high cost of devices, technological constraints, and switching between various learning resources. Some facilitators include enhanced accessibility, sustainability, saving on space and offline capability.	Guthridge & Clinton-Lisell (2023); Cross et al. (2022); Ross & Gilbey (2023)
Instructor and Student Readiness	Instructor training requirements research is currently limited. In general, the preferences expressed by students regarding avatars have been positive, although some issues such as discomfort during simulation were noted. Gender differences in AP gamification preference and support for the presence of avatars were occasionally noted.	Hight et al. (2022); Schaffernak et al. (2020)
Scalability and Implementation Context	It should also be mentioned most studies identified were restricted to a small, academic scenario; with the exception of the AP technology, few implementations in large-scale or commercial contexts were reviewed.	Ross & Gilbey (2023); Cross et al. (2022)
Future Potential and Transformative Impact	The opinions expressed by the educators with regard to VR/AR technology were mostly positive due to the capability that it possessed in terms of engaging learners as well as being affordable and accessible in aviation training, even though there was limited information regarding skill transferability over time and policies thereof.	Thomas et al. (2023); Moesl et al. (2021); Ziakkas et al. (2023)

The thematic synthesis shown in Table 7 presents the application of Virtual Reality (VR) and Augmented Reality (AR) in various phases of aviation training, the difficulties for implementation, and the prospects for the future. VR has most tried for flight simulation, maneuver training, and procedural training, while AR facilitates navigation, pre-flight inspection, and theoretical learning. Both have been viewed more and more as effective (and even possible) replacements for conventional simulators and classroom instruction.

Barriers to implementation, highlighted by the studies included cost of hardware and technical challenges, as well as the need to first develop instructional content to be immersive. Facilitators to implementation included improved access, sustainability, less space needed, and flexibility of learner experience (especially relevant in post-COVID-19 contexts). Instructor disposition is not explored in the literature comprehensively, but students appeared fully engaged and accepting of the technology throughout the studies.

The scalability of immersive learning systems has only been explored through small-scale educational trials, demonstrating a need in future research to explore these systems in more substantial operational and commercial contexts. The majority of the studies analyzed have provided evidence of the immense transformative potential of the VR and AR technology in the aviation field of study, especially regarding engagement, cost-effectiveness, and accessibility; however, further studies are required to validate skill transfer over time in different conditions, formulate regulations, and incorporate VR/AR in organizations.

DISCUSSION

The results of this review support the assertion that immersive technologies, particularly VR and AR, are changing aviation education by improving engagement, procedural learning, and accessibility. From the study conducted, it is evident that there exist consistent increases in knowledge retention and pilot skills, hence confirming the notion that VR systems provide comparable and viable ways of training in lieu of simulator training. Implementing immersive environments goes beyond capability; it requires intentional conceptualizations used in institutional training models and adherent user acceptance over time.

Recent arguments focused on whether VR will have long-term benefits and how these benefits may depend on the flexibility of VR to meet dispositional and operational needs. Weelden et al. (2021), also contributing to the literature base on learner engagement, mentioned the addition of neurotechnology (biometric sensors) to VR in order to quantify learners' cognitive and physiological responses during flight tasks. This could also produce real-time feedback to learners, providing the ability to personalize the learning experience. Adaptive systems could close the gap in transfer of performance between simulation and real-world environments**.** According to Somerville et al. (2026) the VR-assisted Personal Computer Aviation Training Device (PCATD) environment improved training performance transfer for instrument flight training. The researchers studied the essential role of student motivation to virtual reality technology according to their findings. They indicated that feeling driven towards use, along with perceived ease of use, and usefulness are strong predictors of VR adoption. The implication is that immersive technology is a novelty within pedagogy, and emphasis must be placed on a design tied to realism, perceived usability, and felt engagement over time.

The successful adoption of immersive technologies in aviation training at the organizational level requires Jevčák et al. (2024) to establish three fundamental components which include infrastructure and pedagogy and institutional policy. The emerging practices in higher education demonstrate that institutions consider XR technology as a permanent element which supports their digital transformation efforts instead of viewing it as a temporary educational tool. However, according to Moesl et al., (2021), Gorbunov & Li, (2023), there remain several questions that warrant further investigation. These include hardware expenses, need for training for instructors, and visual quality preservation in AR applications.

However, visual fidelity and ergonomics can be considered key elements, since they significantly reduce the level of cognitive load and provide an accurate simulation environment.

Future research will need to target longitudinal experiments that examine how sustained learning and transfer occurs from virtual and augmented reality simulations to real-world flight practices. Adaptive and neurofeedback technology should also be investigated since these innovations have significant potential for integrating personalized learning techniques into a pilot's training regimen. There will be a need for institutional research on curriculum infusion, professional training, and accreditation issues to unlock the power of immersive technology.

CONCLUSION

The findings of this review demonstrate that Virtual Reality (VR) and Augmented Reality (AR) technologies improve the effectiveness, engagement, and accessibility of aviation education and pilot training. Immersive learning systems have progressed beyond the experimental stage and now demonstrate measurable improvements in knowledge retention, procedural skill acquisition, situational awareness, and learner motivation. Nonetheless, for these technologies to be integrated in aviation learning and become sustainable, there is need for solving problems that relate to preparedness of the instructor, infrastructure, standardization, and validation of the training transfer process to practical aviation operations. It is recommended that future studies should emphasize large and longitudinal studies that analyze learning, transfer of training, and the integration of VR/AR technology in aviation regulations and curriculum design.

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