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Pilot Training Modalities in Aviation: A Systematic Review of Their Impact on Safety

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ABSTRACT

Aviation safety remains a global concern, with human error a leading cause of incidents and accidents. This systematic review synthesizes findings from 22 studies (2015–2024) on the impact of pilot training, organized into six themes: simulation-based training, scenario- and task-based training, organizational and academic programs, checklist-, workshop-, and paper-based methods, safety culture and fatigue management, and cognitive adaptation to technology. Simulation and scenario-based training improved situational awareness, hazard recognition, and decision-making under stress. Organizational and academic programs, particularly those embedded in Safety Management Systems, strengthened safety climate and proactive risk management. Checklist and workshop approaches effectively addressed hazardous attitudes and reinforced procedural discipline, while safety culture and fatigue management interventions targeted systemic risks and resilience. Training for cognitive adaptation supported older pilots in transitioning to advanced cockpit technologies. Most studies focused on commercial aviation, with limited evidence from other sectors and few evaluations of long-term outcomes. Future research should integrate these modalities and assess their sustained impact on safety performance.

Keywords: Pilot training, Aviation safety, Human factors, Safety culture, Resilience training

INTRODUCTION

Aviation has long been a critical area of concern due to the high fatality rates associated with accidents (Barroso & Muñoz-Marrón, 2023). These accidents usually arise from human-induced errors (Barroso & Muñoz-Marrón, 2023; Mathavara & Ramachandran, 2022). These human-induced errors include communication breakdowns, flawed decision-making, inadequate situational awareness, and fatigue (Lázaro et al., 2024).

Training plays a crucial role in reducing human-induced errors (Kang-Seok et al., 2014). Airline pilots undergo specialized training designed to teach them how to endure pressure and make sound judgment calls during challenging times (Kang-Seok et al., 2014). As stated by Lázaro et al. (2024), pilot training can be administered using various methods, including the use of high-fidelity simulators, workshops on techniques, scenario-based training, on-the-job training in actual aircraft, or as components within organizational structures such as Safety Management Systems (SMS).

Each modality presents its unique benefits. However, despite advancements in pilot training, aviation incidents and accidents continue to occur. Recent incidents and accidents at major airports in Toronto, Canada; Washington, D.C.; Chicago Midway, IL; and Philadelphia, PA (The Associated Press, 2025; The U.S. Sun, 2025) are stark reminders that serious incidents and accidents remain a pressing concern. This persistent occurrence of incidents and accidents suggests that current training improvements have not fully mitigated operational risks. As a result, there is an urgent imperative for the aviation industry to re-evaluate how pilot training is delivered and to scrutinize the limitations of existing approaches that may be contributing to these unresolved safety issues. The continued occurrence of such events underscores the need to question whether the training pilots receive truly matches the complexity of the challenges they face in real-world operations.

The role of training in aviation safety must be reviewed and strengthened to ensure that its intended benefits are fully realized. This study systematically reviews the contribution of training to aviation safety. The guiding question for this investigation is: How do different pilot training programs and interventions impact aviation safety outcomes?

METHODS

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A literature search was conducted in September 2024 using the PubMed, ProQuest, Scopus, and IEEE Xplore databases, focusing on publications from the past decade (January 2015 to January 2024). Below are the search terms that were used: “safety behavior”, “aviation accidents”, “pilot training”, “aviation training”. Peer-reviewed articles examining the impact of training on safety were analyzed. Two independent reviewers screened the titles and abstracts of all search results to assess the eligibility of each article for inclusion. After removing duplicate entries, the full-text articles of the remaining publications were retrieved for further evaluation. Any inconsistencies regarding article selection were settled through dialogue and mutual agreement between the reviewers. A standardized data abstraction form developed in Microsoft Excel 2020 (Microsoft Corporation, Redmond, WA, USA) was employed for this review. Key information extracted from each eligible article included the following: author names, year of publication, country of origin, methodology, type of training, study participants, data sources, type of aircraft studied, study instruments, impact of training, intervention methods, and critical findings.

RESULTS

Twenty-two relevant studies out of 30,202 records were identified and reviewed. Figure 1 illustrates the selection process. Ten studies focused on commercial aviation, five on general aviation, four on civil aviation, two on military aviation, and one on collegiate/academic flight training. Geographically, twelve studies were conducted in the United States, while the remaining were based in the United Kingdom (three studies), and one study each in Poland, Canada, Australia, Ireland, France, the Netherlands, and one global study. In terms of participant populations, eighteen studies involved pilots (commercial, military, or general aviation), two targeted flight students, one focused on flight instructors, and one involved aviation staff. Regarding survey instruments, eight studies used standardized or validated tools, six studies used ad-hoc survey instruments, and eight studies did not report using any formal or ad-hoc instrument. Additionally, fifteen studies reported participant sample sizes, ranging from 18 to 585 individuals, while seven studies did not disclose sample size. These variations in study design, survey methodology, and sample reporting underscore the heterogeneity across the literature and limit the generalizability and comparability of findings in aviation human factors research. Based on the training modality and focus areas, the 22 studies can be logically grouped into the following six distinct themes:

Simulation-Based Training: Simulation-based training was the most prevalent, featured in eight studies. Lewkowicz and Biernacki (2020) showed that ground-based simulation improved pilots' recognition of spatial disorientation and enhanced safety responses in degraded visual conditions. Clewley and Nixon (2022) used simulator-based sessions to improve pilot recognition of safety events, advocating for enhanced scenario realism. Li, Nichanian et al. (2023) highlighted the need for recurrent simulation-based training to mitigate post-pandemic challenges like proficiency decay and SOP non-compliance. Dehais et al. (2017) employed high-fidelity full-flight simulators and eye-tracking to reveal attention misallocation and visual tunneling during go-arounds, recommending focused training on monitoring behaviors. Pennings et al. (2020) analyzed simulator-based training in Dutch military aviation, showing that increased SD training exposure improved situational awareness and led to more informed curriculum design. Li, Zhang et al. (2023) evaluated the resilience-oriented QCT simulation program and found it improved pilots' stress management and memory categorization. Barroso and Muñoz-Marrón (2023) analyzed ground-based simulator data from global aviation and linked human error to organizational training deficiencies, prompting CRM reforms. Blickensderfer et al. (2015) used paper-based simulation with pre- and post-tests to improve severe weather decision-making and reduce overreliance on cockpit automation.

Scenario-Based and Task-Based Training: Scenario- and task-based training were used in four studies. Mendonca et al. (2018) implemented scenario- based modules targeting hazard perception, aeronautical decision-making (ADM), and risk mitigation. Although pilots showed greater hazard awareness, their application of ADM principles remained inconsistent. Darvishi-Bayazi et al. (2023) combined task-based modules with neurocognitive workload measures, demonstrating that aligning task difficulty with exertion levels improved training outcomes. Sumwalt et al. (2015), in a comprehensive literature synthesis, emphasized the importance of scenario-based simulation to counteract cockpit issues like complacency, automation overreliance, and attention blindness. Clewley and Nixon (2019) implemented concept-based training informed by Categorization Theory, finding that structured exposure to event types under stress enhanced crisis decision-making.

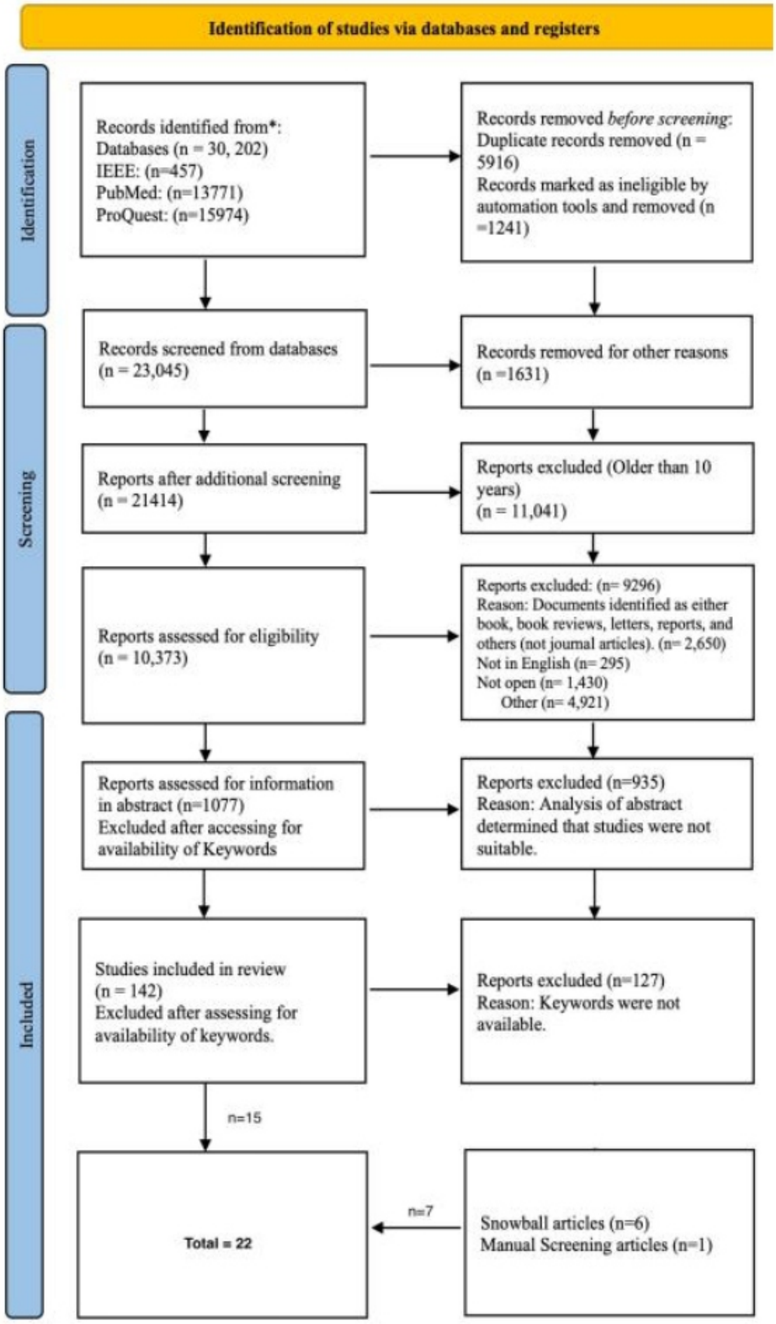

Figure 1: PRISMA diagram.

Organizational and Academic Training Programs: Organizational and academic training programs were the focus of four studies. Byrnes et al. (2022) evaluated a Safety Management System (SMS)-based training program, noting improvements in post-pandemic fatigue risk management and stress resilience. Adjekum et al. (2015) studied collegiate flight training, identifying the influence of age, culture, and organizational pressure on safety reporting behavior. The authors recommended embedding safety values, feedback loops, and trust-building in early training. Ahmed and Scott (2021) advocated for integrating non-technical skills such as emotional intelligence, communication, and hierarchical flattening into both simulated and real-world training environments, guided by frameworks like SHELL. Cahill et al. (2020) examined the impact of an anonymous online survey-based training intervention and found that even experienced commercial pilots benefit from enhanced post-training safety awareness, supporting the use of continuous learning tools in airline operations.

Checklist, Workshop, and Paper-Based Methods: Three studies utilized checklist-, workshop-, or paper-based methods to address cognitive and behavioral dimensions of training. Hyde (2017) evaluated checklist compliance using self-assessment tools and found that training improved pilots' confidence-risk calibration and procedural adherence. Scharf and Cross (2019) delivered workshop training to identify and address hazardous attitudes, showing that targeted interventions could reshape risk orientation and self-confidence. Boyd (2017) reviewed general aviation training related to weather decision-making and found that pilots lacked adequate avoidance behaviors, pointing to deficiencies in thunderstorm-related ADM modules.

Safety Culture and Fatigue Management: Two studies focused on safety culture and fatigue management strategies. Lin et al. (2024) examined resilience and cognitive-emotional regulation in relation to safety culture and advocated for improved fatigue training and dynamic rostering. Chan and Li (2022) studied the impact of training on cross-role organizational safety perceptions and recommended role-specific interventions to harmonize understanding across departments.

Technology Transition and Cognitive Adaptation: Lastly, Kolmos (2019) examined the impact of cockpit technology transition training, especially for older pilots. The study highlighted age-related cognitive adaptation challenges and emphasized the need for tailored training to support older aviators in adjusting to advanced flight systems, bridging generational gaps in technology assimilation.

Table 1 outlines the 22 selected articles.

Table 1: Evidentiary table.

Study	Human Factors	Training Modality	Findings
Lewkowicz and Bierneacki (2020)	Spatial disorientation; cognitive awareness in degraded visual environments	Simulation-based SD training	SD training improved pilot recognition of disorientation.

Continued

Table 1: Continued

Study	Human Factors	Training Modality	Findings
Mendonca et al. (2018)	Aeronautical decision-making; hazard perception; risk mitigation	Scenario-based training	Improved hazard awareness.
Kolmos (2019)	Cognitive adaptation to cockpit technology: age-related learning differences	Training transition in advanced cockpits	Older pilots faced adaptation challenges; need for tailored training
Clewley and Nixon (2019)	Event response accuracy, training-induced behavior under stress	Concept-based training (Categorization theory)	Enhanced pilot recognition and crisis management.
Sumwalt et al. (2015)	Distraction, work-load, automation overreliance, vigilance decline, attention/change blindness, fatigue, complacency	Literature-based analysis for the simulator and practical training	Effective monitoring re- quires hands-on, scenario- based simulator training.
Pennings et al. (2020)	Spatial disorientation, perceptual illusions, crew coordination, and task saturation	Analysis of accident-related procedural and training out- comes.	SD training exposure correlated with higher awareness.
Darvishi-Bayazi et al. (2023)	Cognitive workload, physiological arousal, and effort regulation	Task-based training	Neurocognitive metrics can optimize training workload.
Li, Zhang et al. (2023)	Event recognition accuracy, memory categorization of incidents	Resilience training (QCT program)	QCT training improved stress management and resilience.
Hyde (2017)	Checklist compliance; self-assessment	Checklist for training (Self-assessment)	Reinforcement of checklist adherence through training.
Dehais et al. (2017)	Visual tunneling, attention overload, automation misallocation, and monitoring failures	High-fidelity full-flight simulator training with realistic scenarios	Insufficient monitoring and attention during go-arounds require targeted training on attention allocation and cross-checking.
Ahmed and Scott (2021)	Stress, fatigue, communication failures, emotional intelligence, hierarchy, and situational awareness	Simulated and real-world aviation training environments	Training should incorporate non-technical skills and utilize tools like the SHELL model to enhance safety.

Continued

Table 1: Continued

Study	Human Factors	Training Modality	Findings
Cahill et al. (2020)	Work-related stress (WRS), biopsychosocial health status, coping mechanisms, fatigue risk management	Focusing on new format and Safety Management System (SMS) training	Targeted training and digital self-management tools en- hance pilots' coping strate- gies, self-awareness, and re- silience. It can reduce work- related stress impacts, im- prove well-being, perfor- mance, and flight safety.
Byrnes et al. (2022)	Fatigue risk, alert- ness scheduling, and operational stress	Organizational training (SMS program)	Targeted training and policy adaptations sustained opera- tional safety and informing management strategies in flight training.
Li, Nichanian et al. (2023)	Proficiency decay, SOP adherence, safety system inter- actions	Simulation-based training	FDM revealed that COVID- 19 disruptions caused unstable approaches and exceedances, emphasizing the need for scenario-based training on procedural adherence, threat recognition, and mitigation in abnormal conditions.
Lin et al. (2024)	Resilience: cognitive-emotional stability under stress	Normal training strategies are discussed (safety culture)	Integrating individualized fatigue modeling into crew scheduling reduces cumulative fatigue hours and enhances safety.

Continued

Table 1: Continued

Study	Human Factors	Training Modality	Findings
Boyd (2017)	Risk perception: in-flight decision-making under weather threats	Improvement in training courses	General aviation pilots frequently violate FAA thunderstorm separation minima, often selecting hazardous routes, underscoring the urgent need for enhanced abinitio and recurrent convective weather training.
Chan and Li (2022)	Safety culture perception; cross-role organizational behavior	Training impact via safety culture	Targeted training in resilience, stress management, and adaptive decision-making enhances pilot performance under pressure, reducing cognitive overload and improving safety in complex operational environments.
Adjekum et al. (2015)	Age, cultural differences, safety complacency, lack of trust in reporting systems, and operational pressure	University-based flight training programs	Enhanced safety training that actively fosters positive safety culture perceptions can significantly improve safety behaviors among collegiate aviation students, reinforcing risk mitigation and operational safety standards.
Scharf and Cross (2019)	Risk orientation, self-confidence, and hazardous attitudes	Workshop training	Flight training should incorporate ongoing assessment and discussion of hazardous attitudes, ensuring balanced self-confidence, effective risk management, and safety orientation development.

Continued

Table 1: Continued

Study	Human Factors	Training Modality	Findings
Blickensderfer et al. (2015)	Decision-making when operating in severe weather often leads to overreliance on technology	Paper-based scenarios, pre-post-tests	The training significantly improved pilots' radar knowledge, scenario decision-making, and self-efficacy.
Clewley and Nixon (2022)	Recognition of safety events; variations in pilot knowledge	Simulator-based training	Pilot event knowledge sup- port enhanced scenario-based training in simulators.
Barroso and Muñoz-Marrón (2023)	Human errors, organizational pressures, fatigue, communication failures, and regulatory gaps	Ground-based simulators (e.g., Desdemona)	Accident investigations have shifted training from technical to human factors.

DISCUSSION

This review synthesized evidence across 22 studies to examine how various training modalities influence pilot behavior and aviation safety. It identifies six key themes in pilot safety training: simulation-based training, scenario- and task-based training, organizational and academic programs, checklist/workshop/paper-based methods, safety culture and fatigue management, and cognitive adaptation to technology, each offering distinct contributions to aviation safety. Simulation- based approaches enhance cognitive preparedness by allowing pilots to practice recognition, decision-making, and response under pressure, suggesting that future training should prioritize not just procedural accuracy but cognitive flexibility. Scenario- and task-based trainings bridge theoretical knowledge with operational complexity, reinforcing adaptive behavior and hazard recognition, and should be continually updated to reflect emerging risks such as automation complacency or communication overload. Organizational and academic programs highlight the importance of embedding safety culture early in pilot training and sustaining it through institutional reinforcement, indicating that leadership engagement and reporting-friendly environments are crucial. Low-tech but targeted methods like checklists and workshops remain effective tools for instilling risk-aware behaviors and managing hazardous attitudes, particularly when combined with feedback and reflection. Safety culture and fatigue management training underscore the systemic nature of human error, implying that interventions must include changes to scheduling, team coordination, and cross-role alignment to be truly effective. Cognitive adaptation and technology transition training, particularly for older pilots, call attention to the need for age-sensitive, personalized learning approaches in an increasingly digital cockpit environment.

The implications of these findings are clear: pilot training must evolve from static, one-size-fits-all curricula toward dynamic, behaviorally grounded systems that are personalized, feedback-rich, and organizationally supported. Traditional approaches that emphasize procedural memorization and technical checklists, while foundational, are insufficient for preparing pilots to navigate today's complex, automated, and high-pressure aviation environments. Instead, training should be designed to adapt to the cognitive and emotional demands placed on pilots, using real-time data, scenario variability, and individual learning profiles to optimize both engagement and retention. Simulation technologies, for example, should move beyond fixed-script drills to incorporate adaptive difficulty levels, real-world unpredictability, and embedded behavioral cues, allowing pilots to build situational judgment and resilience over time. Furthermore, feedback mechanisms, whether through instructor debriefs, peer learning, or digital performance analytics, should be structured to provide timely, context-specific guidance that encourages reflection and metacognition.

Policymakers and training organizations also have a critical role to play in operationalizing these insights. Regulatory bodies should incentivize the development and accreditation of adaptive, evidence-based training platforms that integrate human factors science. This includes supporting innovation in training technologies such as AI-driven tutoring systems, physiological workload monitoring tools (e.g., eye-tracking, HRV (heart rate variability) sensors), and virtual or augmented reality environments tailored to different levels of expertise and cognitive load. In parallel, organizations must recognize that effective training is inseparable from safety culture. Embedding training within a psychologically safe organizational climate where pilots are encouraged to report errors, voice concerns, and engage in continuous learning can significantly improve the transfer of training to operational settings.

Equally important is the integration of psychosocial and cultural variables into training evaluation. Current training effectiveness metrics are often limited to knowledge tests or short-term performance scores, which do not capture the deeper behavioral shifts necessary for long-term safety. Future evaluations should include longitudinal monitoring of behavioral markers such as risk reporting, workload management, teamwork quality, and adaptive decision-making. Special attention should also be given to demographic and cultural factors, such as age, gender, cultural background, and rank, which can affect how training is received and applied. Addressing these dimensions can lead to more inclusive and equitable training systems that support all pilots across the experience spectrum.

CONCLUSION

This review highlights the nature of pilot training and its critical role in enhancing aviation safety through six core themes: simulation-based training, scenario- and task-based learning, organizational and academic programs, checklist and workshop-based interventions, safety culture and fatigue management, and cognitive adaptation to technology. Across these domains, the evidence underscores the need to move beyond procedural instruction toward training systems that are adaptive, behaviourally grounded, and contextually relevant. While simulation and scenario-based training enhance situational awareness and decision-making under stress, organizational support and a strong safety culture are equally essential for sustaining these behaviors in real-world settings. Moreover, tailored approaches that address cognitive aging and technological transition will become increasingly important as cockpit environments evolve.

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