

Transforming General Aviation Pilot Training: Integrating Sustainability, Human-Centered Evaluation, and Immersive Digital Innovation

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

Papers Published: The following papers [1–3] are incorporated into Chapters 2, 3, and 4 of this dissertation, respectively.

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Abstract

The general aviation (GA) sector plays a foundational role in training future pilots but faces increasing pressures to modernize amid growing demands for environmental responsibility, instructional effectiveness, and technological adaptation. This dissertation investigates how early-stage GA pilot training, specifically ab initio training, can evolve to meet these imperatives through a multidimensional approach spanning sustainability analysis, learner and practitioner evaluations, and technology integration studies.

Six studies form the core of this work. The first study quantifies the environmental impact of GA flight training in Canada, estimating approximately 30,000 tonnes of annual CO₂ emissions and highlighting opportunities for emissions reduction through greater integration of simulation-based training, while considering additional sustainable strategies. The second study examines student and licensed pilots' perceptions of Canada's GA licensing practices, revealing concerns about the adequacy of flight-hour accumulation as a proxy for competence, alongside broader systemic shortcomings related to outdated instructional methods, inconsistencies in performance assessment, and limited integration of modern technologies—together supporting calls for competency-based reforms. The third study evaluates technology acceptance among student and licensed pilots, identifying cautious receptivity toward assistive training technologies intended to supplement, rather than replace, in-aircraft instruction—albeit tempered by concerns around regulatory inertia, cost barriers, and cultural conservatism. Building on this foundation, Studies 4 and 5 empirically validate AR's instructional utility in high-fidelity simulator and real-aircraft environments, demonstrating enhanced procedural learning and cognitive engagement but also surfacing usability and ergonomic challenges. Study 6 captures Certified Flight Instructors' (CFIs) perspectives on AR integration, revealing both pedagogical potential and pragmatic concerns requiring institutional support.

Synthesizing these findings, the dissertation provides an evidence-based foundation for making GA pilot training more sustainable, competency-centered, and technologically progressive. The work contributes novel empirical insights into an underexplored sector of aviation research, offers actionable strategies for training reform, and highlights the potential for CO₂ reductions by substituting in-aircraft training hours with FSTD- and AR-supported instruction. Ultimately, it advances a vision of GA education that is safer, more effective, and aligned with sustainability goals essential to the future of civil aviation.

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List of Abbreviations

GA	General Aviation
PPL	Private Pilot License
CPL	Commercial Pilot License
ATPL	Airline Transport Pilot License
IATPL	Integrated Airline Transport Pilot License
CFI	Certified Flight Instructor
CO₂	Carbon Dioxide
FSTD	Flight Simulation Training Device
SAF	Sustainable Aviation Fuel
CAT	Commercial Air Transport
FTU	Flight Training Unit
HMD	Head-Mounted Display
AR	Augmented Reality

Chapter 1

Transforming General Aviation Pilot Training: A Multidimensional Integration of Environmental Sustainability, Learner- and Practitioner-Based Evaluations, and Technological Innovation

1.1 Introduction

Over the past several decades, the civil aviation sector has undergone significant transformation, driven by rapid technological advancement, shifting global mobility demands, and increasing environmental accountability. Within this evolving landscape, General Aviation (GA), which encompasses all civil aviation activities outside of commercial airline and military operations, plays a central role in pilot development [4–6]. Among its diverse functions, flight training operations serve as the primary gateway for aspiring professional pilots, forming the initial pathway into the broader civil aviation industry. Today, pilot training in GA is at a critical inflection point, shaped by intersecting pressures: rising demand for qualified pilots, growing calls to reduce aviation’s environmental impact, and the urgent need to modernize instructional frameworks that have remained largely unchanged for decades [1–3,5]. These challenges converge most acutely in the *ab initio* phase (i.e., training that begins with zero flight experience), where the quality and structure of instruction have long-term implications for safety, competence, and professional development. In Canada, this phase is primarily delivered through instructor-led, aircraft-based training as student pilots pursue the Private Pilot License (PPL) and Commercial Pilot License (CPL) as their foundational credentials [7].

Despite its central role in the civil aviation ecosystem, GA pilot training, particularly at the *ab initio* level, has remained largely overlooked in both sustainability research and instructional reform. While considerable research has documented emissions in commercial and military aviation [8–13], there is a notable absence of empirical data quantifying the environmental footprint of early-stage flight training in GA—especially given its fuel-intensive and repetitive nature. This omission represents a critical blind spot in the sector’s ability to align with broader sustainability goals. Recognizing this gap, the first study in this dissertation was designed to conduct a retrospective computational analysis focused on *ab initio* flight training in Canada, aiming to quantify its environmental impact and identify sustainable alternatives that could be meaningfully integrated into current practices.

However, environmental concerns represent only one facet of a broader set of challenges. As this research progressed, it became increasingly apparent that Canada’s GA training framework remains anchored in

legacy assumptions—most notably, the reliance on total flight hours as a proxy for pilot competence [1–5,7,14]. While flight time is a convenient and quantifiable metric, it fails to capture a pilot’s proficiency in the cognitive, procedural, and decision-making skills essential for modern flight operations. Although the literature has noted concerns about the conceptual limitations of hours-based licensing framework [1–5,14–16], there remains limited empirical research grounded in learner- and practitioner-based evaluations that explores how these concerns are perceived or experienced within GA context. This disconnect raises important questions—specifically, whether accumulated flight hours are truly considered a reliable indicator of pilot competence, and whether existing instructional practices are perceived as adequate for preparing pilots to meet the operational and cognitive demands of modern aviation. In other words, advancing environmental reform in GA flight training requires a parallel understanding of how instructional practices are perceived in terms of their pedagogical effectiveness and relevance by those directly involved in the training process. These questions—concerning the validity of flight hours as a competence metric and the perceived adequacy of existing instructional practices—formed the basis for the second study, which shifted focus from the environmental dimensions of ab initio flight training to its pedagogical and experiential foundations. It empirically examined how student and licensed pilots perceive the relevance, effectiveness, and adequacy of current GA training practices, offering insights into how these practices are experienced and interpreted by those currently engaged in or previously exposed to the training process.

The findings pointed to a broader opportunity: to enhance early-stage pilot training through the more effective and scalable use of instructional technologies. While Flight Simulation Training Devices (FSTDs) are formally recognized training tools in GA’s regulatory framework, their adoption remains inconsistent, and the factors contributing to their underutilization—particularly in ab initio training context—are insufficiently addressed in the academic literature [1–5,14,17–20]. This gap is compounded by a broader lack of research on the acceptance and pedagogical relevance of emerging immersive technologies, such as Augmented Reality (AR), within GA. Existing studies on the adoption and integration of immersive training technologies—particularly AR—have predominantly focused on commercial and military settings [21–27], leaving GA largely underexamined. As AR gains attention for its potential to deliver immersive, self-paced, and context-sensitive learning experiences [28–33], its instructional value and feasibility in early-stage pilot education remain open questions. These considerations shaped the design of the third study, which examined learner- and practitioner-based perceptions of both FSTDs and AR—evaluating the perceived instructional role of FSTDs amid inconsistent use and gauging initial receptivity to AR as a novel instructional tool. This technology acceptance study laid the foundation for a series of subsequent empirical investigations that adopted a multi-perspective approach to evaluating the instructional potential of AR in early-stage GA pilot training. The three studies combined learner-centered experimental evaluations, real-

world training environments, and instructor-informed insights to assess AR's instructional effectiveness, usability, and implementation feasibility.

While these six studies collectively chart a pathway for improving early-stage GA pilot training, they are grounded in a recognition of three persistent, system-level challenges: (1) a sizeable but underexamined environmental footprint; (2) an hours-based licensing framework that does not consistently reflect pilot competence; and (3) a slow uptake of instructional technologies. Addressing these interrelated issues is essential to ensuring that GA pilot training evolves in response to contemporary environmental, instructional, and technological demands. Accordingly, the purpose of this dissertation is to address these challenges by generating empirical evidence to support this transformation—advancing early-stage GA pilot training to become more sustainable, instructionally robust, and technology-enabled—through a multi-dimensional research agenda that draws on environmental analysis, learner and practitioner insights, and targeted evaluations of simulation-based tools and emerging instructional technologies such as AR.

1.2 Motivation

The motivation for this research stems from a sustained interest in improving the quality, sustainability, and instructional effectiveness of ab initio pilot training within GA, the entry point for most aspiring professional pilots. Ensuring that early-stage training prepares student pilots for modern operational demands is both a practical necessity and an academic concern.

From an environmental standpoint, the repetitive and fuel-intensive nature of flight training in GA contributes significantly to aviation-related emissions, yet it remains largely absent from national and international sustainability initiatives. Unlike the commercial sector, where emissions and efficiency are closely monitored, GA pilot training has lacked systematic assessment. Addressing this blind spot is critical to developing informed strategies for reducing the associated environmental footprint.

Instructionally, Canada's GA training framework continues to rely on flight time as the central metric of competence. This approach, though simple to administer, fails to capture the multifaceted nature of pilot competence—particularly in cognitive, procedural, and decision-making domains essential for safe and effective piloting. While concerns persist regarding the relevance of training practices, consistency in instruction, and fairness in assessment during flight tests, there remains limited empirical evidence from learners and practitioners in Canada that clarifies how current instructional practices align with real-world performance demands. This lack of direct insight into the training experience underscores the need for further investigation to determine whether current practices are meaningfully aligned with operational readiness.

This research is also driven by a recognition that meaningful instructional innovation must consider the experiences and needs of both student pilots and instructors. Technologies such as FSTDs and AR hold significant promise for enhancing training delivery. However, while FSTDs are already recognized in the regulatory framework, their usage remains uneven. AR, in contrast, is still emerging in this context and requires empirical validation before broader integration. Investigating learner acceptance, instructional effectiveness, and instructor feasibility is essential for evaluating the pedagogical value of these tools in real-world training environments.

Finally, this dissertation is grounded in a commitment to evidence-based reform. Rather than focusing solely on licensing outcomes, it adopts a developmental perspective—emphasizing the significance of early instructional experiences, the need for structured procedural reinforcement, and the importance of aligning training tools with the operational realities of GA. Through this lens, it seeks to advance understanding of how ab initio pilot training can be transformed to more effectively meet the evolving needs of learners, instructors, and the wider GA training ecosystem.

1.3 Research Goals

The overarching aim of this dissertation is to investigate how GA pilot training—particularly at the ab initio level—can be transformed to become more sustainable, instructionally robust, and technologically adaptive. While commercial and military aviation sectors have embraced innovation through simulation technologies, structured data analytics, and immersive instructional tools, GA remains rooted in conventional practices that are often instructor-dependent, resource-intensive, and constrained by an inflexibility in adopting innovation. Given these challenges, this research undertakes a multi-pronged approach spanning environmental, pedagogical, and technological domains. The research goals are structured to build progressively, starting with system-level concerns such as environmental impact and training paradigms and advancing toward the empirical evaluation of emerging technologies through the lens of learner outcomes and instructor perspectives. By integrating these layers, the study aims to inform both academic research and practical improvements within the GA training ecosystem.

The following presents each research goal alongside its rationale and the specific literature gap it seeks to address:

1. **Quantify the Environmental Impact of GA Pilot Training:** While research has extensively examined emissions in commercial civil aviation, little is known about the environmental footprint of ab initio training in GA. There is currently no established emissions baseline for GA pilot training operations in Canada. This goal addresses that gap by undertaking a retrospective computational assessment to estimate CO₂ emissions based on national licensing data and aircraft performance characteristics.

2. **Evaluate Pilot Perceptions of Current Licensing and Instructional Practices:** Given that GA training has remained rooted in conventional practices for decades, there has been limited empirical investigation into how the current licensing framework is perceived by both learners and practitioners in Canada. This goal addresses that gap by exploring how student and licensed pilots view the relevance, quality, and fairness of current instructional and assessment practices, with the aim of identifying applicable shortcomings in the traditional training framework.
3. **Assess the Technology Acceptance of FSTDs and AR in GA Training:** Despite their potential, FSTDs remain underutilized in ab initio training contexts, and AR has yet to be meaningfully explored within this domain. Empirical research examining learner- and practitioner-based perspectives on the instructional value, usability, and implementation feasibility of these technologies in GA remains scarce—particularly at the early stages of pilot training. Moreover, existing studies on AR in aviation have largely focused on commercial and military applications, leaving a significant gap in understanding how student pilots in GA interpret its role and relevance in foundational skill development. This goal addresses these gaps by investigating technology acceptance through student and licensed pilot evaluations of FSTDs and AR, focusing on perceived usefulness, usability, and practical barriers to adoption in GA training settings.
4. **Empirically Evaluate AR’s Instructional Effectiveness:** Building on findings from the technology acceptance study, this goal examines the instructional impact of AR-based training within realistic GA training environments. Despite growing enthusiasm for AR use in education, there remains a lack of controlled, domain-specific studies evaluating its effects on learning in GA flight training, especially in comparison to traditional modalities. This study seeks to address that gap by using structured, learner-centered experimentation to assess how AR influences training outcomes, task performance, and cognitive engagement among ab initio student pilots. The findings are intended to provide evidence on the instructional value of AR as a scalable and sustainable complement to conventional training methods.
5. **Examine Instructor Perspectives on AR Integration in GA Training:** As frontline educators, Certified Flight Instructors (CFIs) play a critical role in the adoption and success of any new instructional tool. The literature has yet to systematically capture how CFIs interpret the risks, benefits, and training implications of AR use in GA training settings. This goal addresses that gap by directly engaging CFIs who have used AR-enhanced instructional materials in a live training context. It examines their views on instructional potential, usability, workload, and institutional feasibility, factors that could enable or inhibit sustainable integration of AR into GA training programs.

Together, these goals form a cohesive research agenda that moves from broad systemic challenges to focused instructional insights. By integrating environmental responsibility, technological innovation, and pedagogical reform, the study aims to contribute a holistic understanding of how GA pilot training can potentially evolve to meet the complex demands of modern aviation education.

1.4 Research Roadmap

This dissertation unfolds through six interlinked studies that collectively advance the overarching research agenda—from system-level assessments to focused instructional evaluations. Study 1 quantifies the environmental footprint of early-stage GA flight training in Canada, specifically CO₂ emissions, addressing a critical but underexplored dimension of sustainability in general aviation. Study 2 explores learner and practitioner perceptions of traditional hours-based licensing practices, evaluating their adequacy and relevance. Study 3 assesses student and licensed pilots' openness to using FSTDs and AR as supplemental training tools, establishing a foundation for instructional technology acceptance. Studies 4 and 5 experimentally evaluate the instructional effectiveness of AR—first in a high-fidelity simulator, then in a real aircraft environment—providing evidence of its pedagogical utility and usability. Finally, Study 6 captures CFIs' perspectives on the instructional value and implementation challenges of AR-based training. Together, these studies generate a cohesive body of empirical evidence to inform the development of sustainable, learner-centered, and innovation-driven pilot training practices within GA.

1.5 Contributions

This dissertation contributes to the academic literature on pilot education by addressing several underexplored areas in GA training—specifically within the ab initio stage. The six studies presented span environmental sustainability, evaluation of instructional practices, and the integration of simulation and immersive technologies. Collectively, they offer a multi-level framework to support instructional reform in GA, grounded in empirical evidence and end-user perspectives.

A summary of the key contributions from each study is as follows:

- **Study 1** introduces a replicable framework for quantifying annual CO₂ emissions from ab initio training in Canada. This offers new data to inform sustainability strategies within GA, an area long overlooked in aviation environmental research.
- **Study 2** presents learner- and practitioner-based insights into the relevance and effectiveness of current training practices. It reveals systemic instructional challenges and supports the case for adopting competency-based training models.

- **Study 3** extends the technology acceptance literature by evaluating perceptions of FSTDs and AR among both learners and practitioners in GA. It highlights the underutilization of simulation tools and examines openness to immersive technology—specifically AR—within the traditionally conservative training environment.
- **Study 4** contributes a structured empirical evaluation of AR’s instructional value within a high-fidelity simulator. It assesses AR’s potential to support procedural learning and cognitive engagement, helping define its role as an assistive tool in early-stage training.
- **Study 5** builds on the simulator study findings by testing AR’s instructional potential in a real aircraft setting. It provides real-world evidence on usability and instructional utility, helping bridge the gap between lab-based research and operational training settings.
- **Study 6** centers on CFIs and explores their perspectives following direct engagement with AR content in a live aircraft context. It identifies instructional, ergonomic, and institutional factors that could affect implementation, providing practice-informed insights imperative to sustainable adoption.

Collectively, these contributions offer insights for enhancing GA pilot training—insights that respond to environmental challenges, reflect the experiences of learners, practitioners, and instructors, and encourage thoughtful integration of instructional innovation. By connecting empirical research with real-world practice, this dissertation contributes to shaping a more adaptive and sustainable training environment.

1.6 Dissertation Outline

This dissertation is organized into eight chapters. Chapter 1 has introduced the context, motivation, research goals, and overall contributions of the work. Chapters 2 through 7 each present one of the six studies, with each chapter structured as a standalone academic paper, including its own introduction, literature review, methodology, results, discussion and study-specific conclusion. Chapter 8 brings the work to a close by drawing connections across studies and situating the findings within the broader landscape of pilot training research and practice.

The following provides an overview of each chapter:

- **Chapter 2** presents Study 1, which lays the foundation with an environmental analysis of flight training in GA, presenting a framework to estimate CO₂ emissions and assess sustainability opportunities.

- **Chapter 3** presents Study 2, explores student and licensed pilots' perspectives on current licensing and instructional practices, offering insights into perceived limitations of the hours-based licensing framework.
- **Chapter 4** presents Study 3, which investigates the acceptance of simulation and AR technologies by GA student and licensed pilots, setting the stage for deeper inquiry into instructional innovation.
- **Chapter 5** presents Study 4, which evaluates AR's instructional impact in a simulated environment, using experimental methods to assess its potential as a training supplement.
- **Chapter 6** presents Study 5, which extends the AR evaluation to a real-aircraft setting, testing usability and learning outcomes in a naturalistic training environment.
- **Chapter 7** presents Study 6, which shifts focus to CFIs and captures their firsthand perspectives, gathered post-intervention, on the feasibility, usability, and integration challenges of AR.
- **Chapter 8** concludes the dissertation by synthesizing findings across all six studies and identifying broader implications for policy, training practices, and future research.

Chapter 2 (Study 1)

Quantifying the Environmental Impact of Ab initio Pilot Training in Canada

2.1 Introduction

The civil aviation industry has significantly grown over the years, with air transport now regarded as one of the world's fastest-growing modes of transportation. Although a severe disruption occurred at the height of the COVID-19 pandemic, the post-pandemic outlook indicates a tremendous demand for air travel. Consequently, the aviation sector is estimated to register an average annual growth of over 4% in the next few decades, with steady expansion expected across all regions [34]. Broadly speaking, sustainability can be defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [35,36]. Therefore, the projections for the aviation sector are sustainable only when growth is embraced in a multi-dimensional manner. To put that into perspective, sustaining this level of growth requires a holistic approach that emphasizes economic, social, and environmental sustainability [37,38]. Economic prosperity, awareness of social consequences, and a commitment to environmental protection are all essential for fostering responsible and ongoing operations. Therefore, for the aviation sector to grow sustainably, the focus must extend beyond infrastructure investments, new technologies, business strategies, and operational enhancements. It is equally important to address the ecological and human consequences resulting from the expansion of aviation activities [39].

Environmental sustainability has been a longstanding, industry-wide issue in aviation, with engine emissions being one of the key focus areas. Aircraft engines release a variety of greenhouse gases and other air pollutants from the burning of aviation gasoline or jet fuel. Carbon dioxide (CO₂), being a direct by-product of combustion, comprises the vast majority of aircraft emissions [40]. Because CO₂ exhibits persistence in the atmosphere [41,42], it is a potent greenhouse gas and one of the main contributors to climate change. Given the strong growth that the aviation sector has experienced in the last few decades, CO₂ emissions from global aviation have risen steadily. International air transportation data indicated that in 2013, global passenger and cargo airline operations contributed 706 million tonnes of CO₂ emissions [43]. By 2019, this figure rose to 920 million tonnes—a surge of over 30% in just 6 years, translating to an average annual growth rate exceeding 4.5% [43]. Given that the global CO₂ emissions for 2019 were estimated at 33.2 billion tonnes [44,45], the global airline operations contribution of 920 million tonnes constituted approximately 2.8% of global CO₂ emissions. However, this emission estimation does not include general aviation due to limited flight tracking and the availability of a comprehensive public

database for general aviation [46–51]. Notably, general aviation encompasses all private and non-commercial aviation operations, excluding routine airline flights and fee-based cargo transport services, as defined by the International Civil Aviation Organization (ICAO) [52]. This distinction is critical as it highlights the broader aviation landscape beyond commercial airlines and cargo services, capturing the essence of private and non-commercial aviation activities that also impact the environment but are less frequently accounted for in global emissions data.

It is worth noting that the widespread grounding of flights during the COVID-19 pandemic in 2020 brought global aviation CO₂ emissions down to an annual estimate of 600 million tonnes. However, as travel restrictions began to ease with the pandemic’s recovery, over a third of this temporary reduction was offset in 2021, resulting in an estimated annual 720 million tonnes of aviation CO₂ emissions [53]. Projections from [54,55] suggest that aviation CO₂ emissions will likely surpass 2019 levels by 2024 and are anticipated to rise rapidly in subsequent years. Given the expected growth in the aviation sector, its current 2.8% share of global CO₂ emissions could potentially increase to 15% by 2050 if environmental issues are not adequately addressed [56–59].

Research [56–59] extensively covers the environmental impact of commercial airline flights; however, a comprehensive evaluation of emissions across the entire aviation sector is essential for advancing sustainability. Recognizing the urgency for sustainability, international aviation agencies have emphasized the need for a detailed understanding of the environmental footprint across different aviation activities. This is crucial for devising effective reduction strategies. Among these, general aviation—comprising private flying, flight training, agricultural aviation, law enforcement surveillance, medical air transport, land surveying, and various non-scheduled commercial operations—stands out as a particularly underexplored area. The quantification of emissions from this wide array of activities is essential for developing targeted strategies to enhance the sustainability of the aviation sector as a whole. This paper narrows its focus to flight training within general aviation, aiming to pinpoint specific emission contributions and explore strategies for reducing their impact, thereby contributing to the advancement of sustainable aviation practices.

2.2 Literature Review and Motivation

Our literature review encompassed several databases, including Google Scholar, BASE, CORE, WorldCat, and RefSeek, using keywords relevant to our focused research area. These keywords encompassed ‘Pilot Training Environmental Impact’, ‘General Aviation Emissions’, ‘Sustainability in Pilot Training’, ‘Eco-friendly Flight Training Practices’, and ‘General Aviation Sustainability Measures’. This approach was driven by the acknowledged need for a deeper dive into the environmental impacts within the general

aviation sector, specifically within the realm of pilot training. Initially, our search returned over 500 articles, indicating a significant volume of work. However, through rigorous screening, we identified 39 papers based on their direct pertinence to understanding and addressing aviation emissions. From these, seven were selected for an in-depth review.

A Transport Canada report [60], developed with contributions from the aviation industry, reviews CO₂ emissions from domestic and international civil aviation operations from 2008 to 2019. It emphasizes the importance of collaborative actions, such as investing in new technologies and enhancing operations to reduce emissions. However, the report lacks a detailed methodology for calculating CO₂ emissions and does not provide a breakdown by sub-sector within civil aviation. Thus, to effectively set ambitious goals and devise strategies for reducing the carbon footprint, precise emissions data and a clear analysis of different aviation sub-sectors are essential.

Wilkerson J et al.'s study offers a detailed analysis of CO₂ and other emissions from global commercial aviation in 2004 and 2006, serving as a baseline for assessing the impact of future technologies, operational improvements, and sustainable aviation fuels [61]. However, it is important that while the paper provides a thorough analysis of aviation emissions for specific years, it only focuses on commercial aviation, not other sectors of civil aviation.

Abrantes I et al.'s study estimates global CO₂ emissions reductions in the aviation sector by 2050, emphasizing the role of advanced aircraft technologies and sustainable aviation fuels [62]. By developing scenarios, the study assesses the impact of these strategies on global air transport fleet emissions. It offers detailed projections of CO₂ reductions in aviation, highlighting the sector's potential to significantly reduce its climate impact. The analysis is based on assumptions regarding technological progress, sustainable aviation fuel production, and adoption rates, which might not reflect the future complexities of these evolving areas. Additionally, the study considers the civil aviation sector uniformly, without providing a detailed breakdown of emissions across different sectors of aviation.

Masiol M and Harrison R's study analyzes aircraft engine emissions and airport-related air pollution, covering data until 2012 [63]. It evaluates civil aviation's environmental impact, focusing on CO₂ and other pollutants. The study highlights the sector's expansion due to developing economies and globalization, addressing the environmental challenges of emissions at cruising altitudes and air quality near airports. It stresses the importance of accurately estimating and mitigating aviation CO₂ emissions. While it does not provide new CO₂ emission estimates for aviation, it synthesizes existing research to underscore the significance of aviation emissions on both global and local air quality and the overall environmental footprint of civil aviation.

Zhou W et al.'s study estimates and analyzes future CO₂ emissions from China's civil aviation sector from 2015 to 2030 using scenario analysis [64]. This includes factors like low carbon jet fuel adoption, technological advancements in fuel efficiency, and rising air traffic demand. The study also reviews historical emissions from 1980 to 2013, noting a significant increase due to air traffic growth, to set a baseline for future growth projections. By providing a detailed analysis of historical and future emissions and suggesting policy measures for reduction, the study contributes to aviation CO₂ emissions literature. However, its focus is solely on China's civil aviation.

Puliafito S's study compiles a comprehensive CO₂ emissions inventory for Argentine civil aviation, covering both domestic and international flights from 2001 to 2021 [65]. It uses a methodology that considers flight altitude, aircraft types, and airline data, assessing efficiency improvements and sustainable aviation fuel production potential, with implications for environmental policy and industry practices. However, the study's generalized approach does not account for the specific operational and efficiency differences across aviation sub-sectors like commercial airlines, cargo flights, and general aviation, potentially obscuring variations in emissions intensity and reduction opportunities.

Quadros F et al.'s study estimates global civil aviation CO₂ emissions from 2017 to 2020, utilizing ADS-B receiver flight data, the BADA 3.15 model for aircraft specifics, and an international database for engine emissions [66]. This approach calculates the pollution generated by airplanes worldwide during this period. However, limitations include the lack of ADS-B transmitters on some aircraft and uneven geographical ADS-B coverage, possibly leading to emission underestimations in sparsely covered areas. Additionally, while the study showcases global estimates, it does not attempt to capture emissions variations across distinctive sectors within civil aviation.

Our literature review highlights a notable research gap regarding the estimation of CO₂ emissions within the civil aviation sector, both in Canada and globally. Existing research studies provide estimates that generalize the civil aviation sector, ignoring the nuanced differences of sub-sectors like general aviation. This lack of differentiation is critical, as a sub-sector like general aviation, covering a range of non-commercial and private operations, varies significantly from commercial aviation in fleet composition, operational practices, and fuel efficiency. Such variations imply that general aviation may have distinct CO₂ emissions trends, which are likely overlooked in broader sector analyses. Also, given the limited examination of sub-sectors within the civil aviation sector, the undertaking of estimating and understanding emissions related to operations in a specific sub-sector like general aviation remains largely unexplored. Consequently, the uniform approach to civil aviation emissions research may lead to generalized conclusions that fail to capture the sector's varied operational landscapes, potentially masking significant variations in emissions intensity and reduction opportunities across its respective sub-sectors.

To address this research gap, our study underscores the importance of dissecting emissions by sub-sector to uncover distinct challenges and opportunities for emissions mitigation. By zeroing in on general aviation, with a particular focus on flight training operations, we seek to determine the CO₂ emission contributions in this under-researched area and explore strategies for reducing their impact. This focused approach is imperative for creating holistic strategies that enhance the aviation sector's sustainability, thereby contributing significant insights to the progress of eco-friendly aviation practices.

2.3 Scope and Objective

Student pilots pursuing a Private Pilot License (PPL) or a Commercial Pilot License (CPL) in Canada must complete ground school, pass a written test, receive the requisite flight training, log the applicable number of flight hours, and pass a flight test administered by a certified examiner to obtain their license. Current training practice mainly uses the method of instructor tutoring, which has mostly been the same over the past decades.

The term 'ab initio', derived from Latin, means 'from the start' and is used to describe initial flight training programs for student pilots with no prior flying experience. Student pilots acquire pertinent aviation knowledge, such as rules of the air, navigation, and aircraft systems, in classrooms. Subsequently, they develop their flying skills through dual flight training with an instructor and solo flight in aircraft. Consequently, flight training contributes hundreds of thousands of tonnes of CO₂ emissions every year. While the demand for new pilots dropped significantly in 2020, the civil aviation industry foresees a notable uptick in the need for new pilots as air travel recovers post-pandemic. A Pilot Demand Outlook [67] published by CAE Inc. projects that between 2020 and 2030, Canada and the USA will require over 65,000 new pilots, while globally, the demand is set to exceed 264,000 new pilots. Age-based retirement, attrition, and fleet growth are projected to be the main drivers of the increasing demand for pilots. Although the training of airline pilots has increasingly relied on simulators, ab initio pilot training will still produce substantial emissions over at least several decades if it still follows the current practice.

This study examines CO₂ emissions originating from ab initio flight training within Canada's general aviation sector, covering the journey from the initial stages to the attainment of both the PPL and the CPL. While numerous studies in the past have estimated airline emissions, this study distinguishes itself by specifically analyzing the environmental impact of ab initio training in the general aviation sector and quantifying it in terms of CO₂ emissions. This area remains unexplored in the current body of literature, and quantifying these emissions addresses that research gap. To assess CO₂ emissions associated with ab initio flight training, the analysis in this study focuses on Canada as the geographical area of interest and relies on Transport Canada pilot licensing regulations and Canadian civil aviation licensing statistics to

draw data-driven conclusions. The primary objective of this study is to provide methodological research to establish a baseline for CO₂ emissions associated with ab initio flight training.

2.4 Method and Materials

2.4.1. Mathematical Equation

A mathematical equation was developed to estimate the annual CO₂ emissions arising from flight training operations. This model incorporates a set of dependent variables, each playing an important role in determining the overall emissions. The mathematical model, along with a detailed description of each variable involved and the resulting output, is outlined below as Equation (1).

$$\text{Annual Flight Training CO}_2 \text{ Emissions (average)} = \bar{H} \times \bar{E} \times \bar{C} \times \bar{L} \quad (1)$$

where,

$\bar{H}$ = Flight Training Hours

$\bar{E}$ = Efficiency Factor

$\bar{C}$ = CO₂ emitted per flight hour

$\bar{L}$ = Annual Number of Licenses Issued

The variable $\bar{H}$ represents the flight training hours, quantifying the average amount of hours spent on flight training operations over a year. The efficiency factor $\bar{E}$ variable accounts for variations in flight performance due to factors such as aircraft maintenance quality, pilot proficiency, weather conditions, or the specific nature of training maneuvers executed during flight hours. This non-dimensional coefficient adjusts the emissions estimate to reflect the operational efficiency or inefficiency of an aircraft relative to its baseline fuel consumption rate. The variable $\bar{C}$ represents the CO₂ emission rate per flight hour, specifying the average quantity of CO₂ produced for every hour of flight training. Meanwhile, the annual number of pilot licenses issued $\bar{L}$ denotes the average count of pilot licenses granted each year. Each of these is then multiplied together, with a resultant figure representing the average annual flight training CO₂ emissions, offering an estimate of the total carbon dioxide emissions generated by flight training operations over the span of a year. This mathematical equation considers not only the total training hours but also factors in the execution efficiency and the environmental impact measured through CO₂ emissions per training hour, alongside an influx of new pilots into the aviation sector.

2.4.2 Flight Training Hours ($\bar{H}$)

This study reviews private and commercial pilot license training with fixed-wing airplanes, the most common training pathway for aspiring pilots in Canada, and discusses the associated environmental impact. These training prerequisites strictly adhere to Transport Canada's regulatory standards, which mandate the required minimal numbers of flying hours for the development of psychomotor skills. In practice, students usually need more hours than the required minimal numbers to meet proficiency standards.

Pilot licensing in Canada is a staged process. In the context of private pilot license (PPL) requirements, the Canadian Aviation Regulations [68] indicates that a student pilot must complete a minimum of 45 hours of private pilot-focused flight training in airplanes. Only a maximum of 5 h out of these 45 h can be completed in an approved flight simulation training device (FSTD). It should be noted that FSTD is an umbrella term used to refer to any synthetic training device or simulator, and aviation authorities must formally certify each FSTD before it can be used for pilot training. While the minimum regulatory flying requirements could equate to a total of 45 h (assuming no FSTD utility), there is emergent evidence [69–73] that the total flight hours typically accumulated by student pilots to obtain their private pilot license is closer to an average of 65 h. The process of determining this average flight duration of 65 h involved examining training record testimonies from multiple flight schools across Canada. This evaluation also incorporated insights reported by experienced flight instructors, ensuring a wide-ranging representation of perspectives and experiences. This average represented the overall number of flying hours, including both dual instruction training (in-aircraft training with a student pilot and instructor) and solo flight training (in-aircraft training with only the student pilot). The dynamic interaction of individual differences, such as variations in student pilots' abilities and aptitudes, influences the need for additional hours beyond the regulatory minimum requirement [74]. Therefore, an estimated average of 65 h for PPL aircraft training was identified to be a consistent estimate and was consequently used in this study. This decision was made due to the lack of sufficient data to accurately estimate the range or distribution of these training hours.

With respect to commercial pilot license (CPL) requirements after obtaining PPL, Canadian Aviation Regulations (CARs) [68] require CPL student pilots to complete a minimum of 65 h (dual instruction and solo flying combined) of commercial pilot flight training in airplanes. Only a maximum of 10 h out of these 65 h can be completed in an approved FSTD. However, in order to be eligible for the CPL flight examination, a student pilot must accumulate a minimum of 200 h of overall flight experience, with a minimum of 100 h as pilot-in-command (PIC). Flight hours gained as part of both PPL and CPL training can be applied towards fulfilling this 200-h minimum criterion. PIC refers to when a student pilot is the sole manipulator of the flight controls and also bears full responsibility, authority, and accountability for the operation and safety of the aircraft during flight time. PIC hours do not necessarily involve solo flying,

though; hence, PIC hours can also be logged with a two-person or more crew on a flight, with the student pilot serving as PIC. However, depending on the student pilot's ability, aptitude, and skill level, the regulatory minimums of flight hours may not always suffice for them. Consequently, a higher number of training flight hours are undertaken to develop the necessary proficiency to commercial license standards. An exploratory study [75] examined the relationship between additional training hours and various factors, including individual learning curves. This investigation analyzed data from 688 commercial pilot license issuances, providing a basis for estimating the average duration of extended flight training. The study revealed that student pilots had amassed a significantly higher number of training hours, surpassing the mandated regulatory minimum by 26%. Hence, an average length of flight time accumulated for CPL (after obtaining PPL) can be determined to be 195 flight hours (155 h increased by 26%). These 155 h represent 65 h from CPL training (assuming no FSTD utility) and an additional 90 flying hours to accumulate the necessary PIC experience while meeting the minimum overall flight experience requirement of 200 h. Due to the absence of sufficient data to support an accurate estimation of the range or distribution of these training hours, we have opted to adopt 155 h as the estimated average for CPL aircraft training hours.

2.4.3 Efficiency Factor ($\bar{E}$) and CO₂ Emitted per Flight Hour ($\bar{C}$)

To estimate the CO₂ emissions for each hour of flight training, it is essential to first establish the rate of fuel consumption. The fuel consumption rate is a parameter influenced by various factors, including aircraft type, engine specifications, training maneuvers, and weather conditions. Although there are various airplane types available for flight training, a list of commonly used training aircraft was established after making inquiries at over 30 Canadian-based flying schools. Known to have the right combination of features and flight training characteristics along with simple systems and procedures that are ideally suited for flight school students—these aircraft bolster a reputation of being among the most common types of trainer aircraft used by flight schools not just in Canada, but also globally [76–78]. For simplicity, we applied an Efficiency Factor of 1 to represent average efficiency, where values above or below 1 denote conditions with increased or decreased fuel use. The application of an Efficiency Factor of 1 aid in establishing a baseline for comparison and simplifies the calculation process while acknowledging that real-world conditions may vary. Building on this simplification and employing the standard cruising power typical at optimal conditions, the fuel consumption rates at cruising altitude for the commonly used aircraft models were determined. These are detailed in Table 1. Although different flight maneuvers—such as landing, slow flight, takeoff, and climb—could have varying fuel consumption rates, either lower or higher than the rates at cruising altitude, the limited availability of data concerning these diverse maneuvers and their associated fuel consumption rates made a thorough investigation of these scenarios unachievable. This led to the decision not to delve further into these conditions.

Table 1. Types of aircraft used for flight training and their fuel burn rates.

Aircraft Type	Associated Conditions		Fuel Burn Rate (AVGAS) (U.S. Gallons Per Hour, gph)
Cessna 172S	6000 ft pressure altitude and at standard temperature	2600 RPM @ 73% rated power	9.9 [79]
Cessna 150M		2700 RPM @ 73% rated power	5.4 [80]
Cessna 152		2500 RPM @ 75% rated power	6.1 [81]
Diamond DA20 C1		2800 RPM @ 70% rated power	6.5 [82]
Diamond DA40-180		2400 RPM @ 65% rated power	8.5 [83]
Piper Archer (PA-28-181)		2605 RPM @ 75% rated power	11 [84]
Piper Warrior (PA-28-161)		2660 RPM @ 75% rated power	11.4 [85]
Average			8.4 gph

Given the variability in fuel consumption rates among commonly used aircraft, an estimated average fuel burn rate of 8.4 gph (approximately 32 L per hour) was derived from training aircraft data in Table 1. This estimate encompasses variations from 5.4 gph to 11.4 gph across different aircraft models. The selected average fuel burn rate of 8.4 gph effectively accommodates the variability in fuel efficiency observed across various models and is consistent with industry insights, thereby providing a well-grounded and balanced foundation for estimating CO₂ emissions in flight training contexts. Therefore, the utility of this rate was deemed a reasonable estimate, mirroring the spectrum of rates observed in commonly utilized training aircraft.

With every liter of aviation gasoline (avgas) burned, about 2.2 kg of CO₂ [86] could be generated, subsequently producing an average of 70.4 kg of CO₂ per hour (32 L per hour × 2.2 kg), with a range from 44.9 kg to 94.9 kg given different aircraft models. For accurate calculations, understanding the specific avgas composition and combustion efficiency is necessary. Nevertheless, the simplified estimate of 2.2 kg of CO₂ per liter of avgas burned is practical. This estimate, based on Avgas's carbon content and typical piston engine combustion efficiency, aligns with combustion principles and Avgas's chemical properties [86]. Although it may not perfectly match every avgas variation, this figure serves as a justified baseline for assessing environmental impacts. It is also worth mentioning that a small proportion of general aviation aircraft, such as the DA40 NG, now operate on jet fuel rather than traditional avgas. However, these aircraft were not factored into our calculations due to their low prevalence (less than 10% of the fleet) in flight schools [87,88].

2.4.4 Annual Number of Licenses Issued ($\bar{L}$)

To determine the annual number of pilot licenses issued across Canada, we collaborated with Transport Canada to obtain this data. Data sourced from Transport Canada revealed the number of private and commercial pilot licenses issued over a 23-year period (2000–2022), as illustrated in Figure 1. On average, 2590 private and 1298 commercial pilot licenses were issued annually.

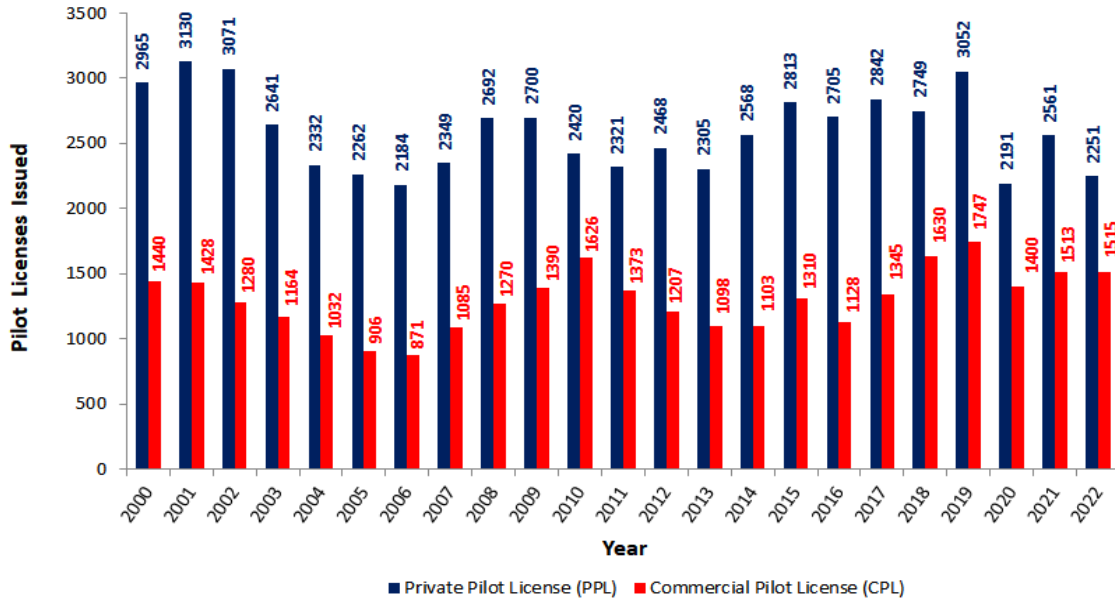


Figure 1. Historical issuances of licenses in Canada
(Source of license data used: Transport Canada, 2023).

2.5 Results and Analysis

2.5.1 Annual Flight Training CO₂ Emissions

Utilizing the previously established average flight training durations—65 h for the PPL and 195 h for the CPL—along with an Efficiency Factor of 1, an average CO₂ emission rate of 70.4 kg per flight hour, and considering the annual issuance of approximately 2590 private and 1298 commercial pilot licenses, we calculated the CO₂ emissions associated with obtaining each type of license using Equation (1), as shown below.

$$\begin{aligned}
 & \text{PPL Annual Flight Training CO}_2 \text{ Emissions (average)} \\
 &= 65 \text{ hours} \times 1 \times 70.4 \frac{\text{kg}}{\text{hr}} \times 2590 \text{ licenses}
 \end{aligned}$$

CPL Annual Flight Training CO₂ Emissions (average)

$$= 195 \text{ hours} \times 1 \times 70.4 \frac{\text{kg}}{\text{hr}} \times 1298 \text{ licenses}$$

On average, a little over 11,852 and 17,819 tonnes of CO₂ were contributed every year from PPL and CPL flight training respectively. This brings the average annual flight training CO₂ emissions to 29,671 tonnes in Canada, which can be rounded to approximately 30,000 tonnes. Using an average fuel burn rate ranging from 5.4 gph to 11.4 gph for different aircraft models, these flight training CO₂ emissions of 30,000 tonnes can be reported with a range from 19,000 to 40,000 tonnes.

To support replicability of the emissions estimation framework, Table 2 summarizes the key parameters and baseline assumptions used in the analysis, including training milestones, common aircraft characteristics, and fuel consumption rates.

Table 2. Key parameters and assumptions used in CO₂ emissions estimation

Parameter	Baseline Value / Assumption
Average flight hours for PPL	65 hours
Average flight hours for CPL (post PPL)	195 hours
Efficiency factor	1 (indicates average efficiency; values >1 mean higher fuel use, <1 mean lower)
Fuel burn rate (avgas)	32 Liter per hour
CO ₂ emissions per Liter of aviation gasoline (avgas)	2.2 Kg
CO ₂ emissions per flight hour	70.4 Kg
Annual license issuances for PPL	2590 (average number of licenses per year)
Annual license issuances for CPL	1298 (average number of licenses per year)

A sensitivity analysis was also conducted by varying the average Flight Training Hours by ±10%, 20%, and 30% to assess the corresponding impact on annual CO₂ emissions from flight training. Among the variables in the mathematical model used to estimate CO₂ emissions, Flight Training Hours was selected for sensitivity testing due to its practical variability across training contexts. In practice, Flight Training Hours can potentially be influenced through improved instructional design, technology integration (e.g., simulation use), or curriculum optimization—making it both a meaningful and actionable parameter for emissions mitigation. As shown in Table 3, CO₂ emissions range from approximately 20,770 to 38,572 tonnes annually under the tested scenarios. Even with a 30% reduction in the average Flight Training Hours, CO₂ emissions remain substantial—exceeding 20,000 tonnes—while a 30% increase pushes the total above

38,000 tonnes. This range brackets the CO₂ emissions estimate and reinforces that the environmental impact of flight training is significant under a wide range of realistic conditions.

Table 3. Sensitivity analysis on variations in average Flight Training Hours

Change in Flight Training Hours (%)	Adjusted Flight Training Hours		Annual Flight Training CO ₂ Emissions (tonnes)
	PPL	CPL	
-30	45.5	136.5	20770
-20	52	156	23737
-10	58.5	175.5	26704
0% (Baseline)	65	195	29671
10	71.5	214.5	32638
20	78	234	35605
30	84.5	253.5	38572

2.5.2 CO₂ Emissions Trend Analysis

The estimated CO₂ emissions from both PPL and CPL training have experienced considerable fluctuations over the years, detailed in Figure 2 and discussed below.

PPL emissions exhibited an initial period of fluctuation from 2000 to 2006, beginning at 13,567.84 tonnes of CO₂ in 2000 and experiencing variations, including a slight increase in the first two years, followed by a gradual decrease to reach 9993.98 tonnes in 2006. This period indicates a mixed trend with both increases and decreases, ultimately leading to a decrease in emissions by 2006. The year 2007 marked a turning point, with emissions rising to 10,749.02 tonnes, signaling the start of an erratic upward trend. This trend included fluctuations with slight increases and decreases, reaching a modest peak in 2009 at 12,355.2 tonnes before a decrease in 2010 to 11,073.92 tonnes, illustrating the variable nature of PPL emissions during this period. From 2010 to 2017, the emissions pattern remained variable, with a notable decrease following 2010, reaching a low in 2013 at 10,547.68 tonnes. The period then saw gradual increases, culminating in a more consistent upward trend through to 2019, peaking at 13,965.95 tonnes. This rise was marked by a gradual increase in emissions, reflecting a period of growth in PPL activities. The impact of the COVID-19 pandemic was significantly felt in 2020, with emissions plummeting to 10,026.02 tonnes—a sharp decline reflecting the global downturn in aviation activities. A partial recovery was observed in 2021, with emissions increasing to 11,719.14 tonnes, followed by a decrease in 2022 to 10,300.58 tonnes. This recent period highlights the challenges faced by the aviation sector, including PPL training, in the wake of the pandemic, with initial signs of recovery tempered by subsequent decreases.

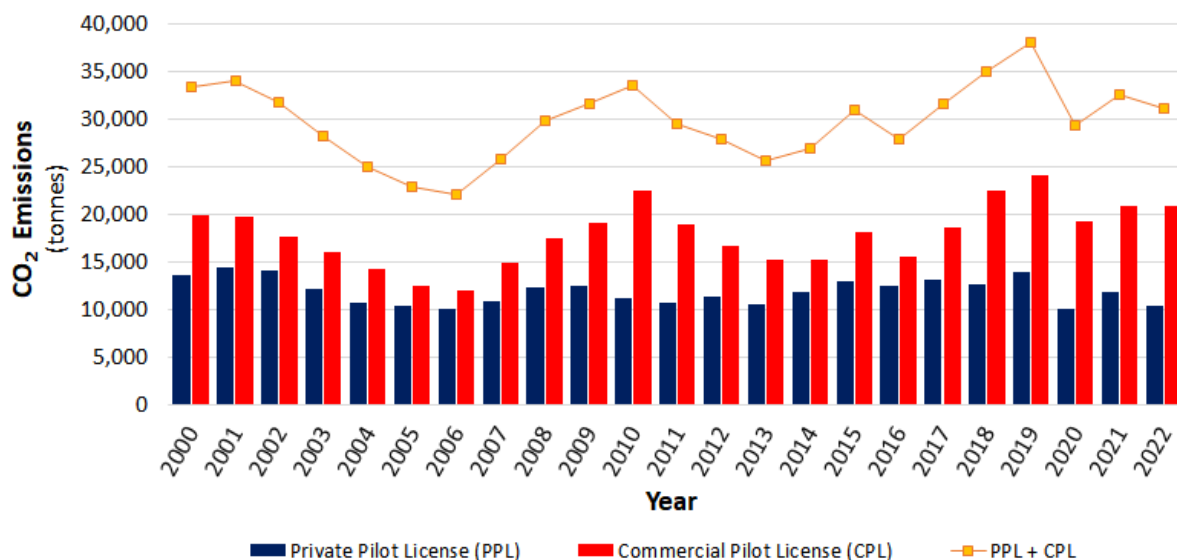


Figure 2. Estimated CO₂ Emissions for PPL and CPL Training.

CPL emissions saw a downward trend from 2000 to 2006, starting at 19,798.73 tonnes in 2000 and decreasing each year to reach 11,975.48 tonnes in 2006, indicating a period of declining emissions. This was followed by an increase in 2007, with emissions rising to 14,917.80 tonnes, marking the beginning of a general upward trend that continued with fluctuations through 2010, which saw a significant increase, culminating in 22,356.07 tonnes—a 16.98% increase from 2009. From 2010 to 2017, the trend was more mixed. After reaching a peak in 2010, emissions dropped significantly by 2011, followed by further decreases until a low in 2013. Emissions then increased slightly in 2014, followed by a more substantial rise in 2015, leading to another period of growth that peaked in 2019 with 24,019.71 tonnes, highlighted by a 19.24% increase in 2017 compared to 2016. The year 2020 observed a pronounced decline, with emissions decreasing to 19,248.77 tonnes—a 19.86% decrease, reflecting the global impact of the COVID-19 pandemic on aviation activities. However, there was a partial recovery in 2021, with emissions increasing to 20,802.42 tonnes, an 8.07% increase, and stabilization in 2022 with a slight increase to 20,829.92 tonnes, representing a marginal 0.13% increase from the previous year. This period indicates a rebound and stabilization in CPL emissions after the pandemic's initial impacts.

The total emissions from PPL and CPL training from 2000 to 2022 show a trend of fluctuation, characterized by periods of both decline and growth. From 2000 to 2006, the data show a gradual decrease in total emissions, starting at 33,366.57 tonnes in 2000 and reaching a low of 21,969.47 tonnes in 2006. This period signifies a downward trend in total emissions from both PPL and CPL training. The year 2007 marked the beginning of a recovery phase, with emissions increasing to 25,666.82 tonnes. This recovery continued, with notable growth through to 2010, reaching 33,429.99 tonnes and indicating a resurgence in

aviation training activities. However, from 2011 to 2013, a period of decline was observed once again, with emissions dropping to 25,644.21 tonnes by 2013. From 2014 onwards, a notable recovery and growth phase occurred, peaking in 2019 with emissions at 37,985.66 tonnes. This represents the highest level of emissions within the provided dataset, showcasing a period of increased training activity. The impact of the COVID-19 pandemic was clearly seen in 2020, with emissions dropping significantly to 29,274.78 tonnes. A partial recovery in 2021, with emissions rising to 32,521.55 tonnes, was observed, but a slight decrease in 2022 to 31,130.49 tonnes suggests that the recovery may be facing challenges.

The observed year-to-year changes in PPL and CPL emissions can be regarded as multifaceted, reflecting not merely changes in the issuance of licenses but can also intertwine with broader economic factors impacting the pilot training sub-sector. Fluctuations in fuel prices directly influence flight training expenses, challenging the affordability and accessibility of pilot training. The economic stability of aviation training institutions can play a role as well; their financial health determines the extent to which they can invest in modern training aircraft and other technologies. Such advancements not only enhance the quality and efficacy of training but also hold the potential for reducing CO₂ emissions. Furthermore, the COVID-19 pandemic has had a profound impact, with the noticeable downturn in 2020 predominantly linked to the widespread disruptions in flight training operations caused by travel restrictions and lockdown measures. This period stands out as a critical juncture, underscoring the vulnerability of the aviation training sector to global crises and emphasizing the importance of resilience and adaptability in the face of unprecedented challenges.

2.6 Discussion

2.6.1. Research Impact

The study provides a novel and significant insight into the environmental impact of ab initio pilot training in Canada, a previously underexplored area within general aviation's CO₂ emissions footprint. Establishing that each hour of flight training releases approximately 70.4 kg of CO₂, and with annual emissions estimated to be around 30,000 tonnes—ranging between 19,000 to 40,000 tonnes—it not only fills a gap in our understanding of the civil aviation sector's broader environmental effects beyond commercial flying but also emphasizes the need for integrating sustainable practices in the aviation education and training sub-sector. This research contributes to the discourse on aviation sustainability, urging a comprehensive view that includes all aviation activities in strategies to mitigate environmental impact. It highlights the importance of rethinking how pilot training is conducted as part of the industry's commitment to achieving net-zero emissions by 2050. Addressing this challenge necessitates overcoming technological, regulatory,

and economic barriers, pointing towards an integrated approach that involves all stakeholders in the aviation ecosystem.

2.6.2. Comparison with Other Aviation Emission Sources

CO₂ emissions from flight training constitute a minor segment (<1%) of the overall aviation emissions in Canada, juxtaposed against the larger contributions from commercial flights, cargo transport, and military operations. The variation in yearly trends of flight training emissions diverges from other aviation sources, influenced by distinct operational demands and varying impacts from economic fluctuations. Within the broader context of general aviation's environmental impact, flight training emissions, while only a small fraction of overall aviation emissions, are integral to understanding the sector's total CO₂ footprint. Therefore, this research accentuates the imperative of incorporating flight training into the broader dialogue of general aviation sustainability, advocating for a comprehensive decarbonization strategy that emphasizes both current flying practices and training future pilots with eco-friendly practices.

2.6.3 Technologies for Sustainable Ab Initio Training

Canada's existing pilot licensing and flight training standards are based on specific hour requirements. Student pilots must amass a prescribed number of flight hours for their flight test qualification. However, this approach may not encompass the full training necessary for proficiency, including exposure to diverse scenarios such as in-flight emergencies, equipment malfunctions, or severe weather conditions. Flight schools lack incentives to embrace innovative training methods such as FSTDs since the regulations do not mandate their use, thus preventing flying schools from incurring the financial burden of acquiring FSTDs, which can cost hundreds of thousands of dollars. The underutilization of FSTDs by student pilots can result in extended flight training periods to meet proficiency standards, consequently resulting in additional CO₂ emissions. Therefore, a more cohesive integration of FSTDs into pilot licensing and training standards is recommended to enhance training quality.

Battery-powered electric aircraft provide a solution to reduce CO₂ emissions from general aviation flight training. They also eliminate the use of leaded fuel, which can have adverse health effects, especially on children exposed to lead emissions. Electric aircraft, such as the Velis Electro, can provide cost-effective short-distance flight training with reduced maintenance [89]. Although electric aircraft face challenges with battery life, ongoing developments are expected to improve their performance. In addition to electric aircraft, alternative fuel solutions like sustainable aviation fuel (SAF) can be considered to reduce CO₂ emissions. These biofuels can cut emissions by up to 80%, and their use in small piston-engine planes is being explored [90–93]. Despite challenges, such as limited production and high costs, SAF has the potential to reduce the environmental impact of flight training as the industry develops further.

2.6.4 Limitations

The analysis in this study is conducted in accordance with the general aviation flight training standards for private and commercial pilot licenses currently being practiced in Canada. While both private and commercial pilot license training primarily utilize single-engine aircraft for flight training, the curriculum at different flight schools may integrate the option for a multi-engine rating as part of the commercial pilot license training. The analysis presented in this study assumes aspiring pilots opt only for the single-engine rating; thus, the analysis exclusively considers single-engine flight training aircraft. Attaining a multi-engine rating generally necessitates up to 10 h of additional dual-flight training for adequate preparation [68]. This would have led to an increment in the total flight training hours associated with CPL, resulting in additional CO₂ emissions.

The cruise flight fuel burn rates utilized in this study are based on aircraft performance data provided by airplane manufacturers. Typically, these rates are ascertained from staged testing on new engines and may not wholly reflect the performance of operational aircraft. Furthermore, the fuel burn rates utilized pertain to specific standard cruise operation conditions, such as maintaining a constant altitude and speed, adhering to nominal weight, observing standard temperature, experiencing favorable weather conditions with no crosswinds, employing ideal pilot flying techniques, receiving optimum flight management from Air Traffic Control (ATC), maintaining a set rated power setting, among others. However, in real-world scenarios, an airplane may encounter continuous variations in fuel burn rate as the fuel consumption rate could be influenced by a multitude of factors.

The analysis in this study leverages the most commonly utilized aircraft to depict flight training activities across Canada, yet it recognizes that it does not cover the entire array of aircraft used by flying schools, especially those that employ unique or less common types. Furthermore, the analysis is based on a specific variant for each identified aircraft type and model, despite the fact that many models have multiple variants with distinct fuel consumption rates. This means flying schools might use a variety of aircraft variants, which could differ from those analyzed in our study. However, we derived an average fuel consumption rate of 8.4 gph from a wide range of fuel burn rates, spanning from 5.4 to 11.4 gph. While the precise variation can depend on the specific model differences and operational settings, it is generally understood that fuel burn rates for Cessna aircraft variants typically fluctuate by ± 0.5 to ± 1 gph [79–81]. In contrast, Diamond and Piper variants may experience a larger variation of ± 1 to 2 gph [82–85]. When considering these best and worst performance variations, using different variants of the aircraft models used in this study could theoretically adjust the estimated average fuel consumption rate of 8.4 gph by approximately ± 0.8 gph. Consequently, the selected average of 8.4 gph can be considered a reasonable estimate, suggesting

that our conclusions should remain relevant even when taking into account a broader spectrum of aircraft types and their variants.

Pilots are required to participate in recurring flight training [68] at regular intervals. However, the frequency of this training can fluctuate based on each pilot's individual circumstances. Experienced pilots who regularly engage in flying activities to maintain their skills may not need additional recurrent training. On the other hand, less active pilots or those whose skills have deteriorated may necessitate more recurrent training, potentially involving dual-instruction flight training to maintain safety and proficiency in their flying activities. Because of the unavailability of adequate data to estimate CO₂ emissions stemming from recurrent flight training, we have chosen to exclude it from our CO₂ emission calculations.

2.6.5. Future Research

Simulation training has been a staple in pilot training programs and has been utilized by aviation schools for several years [94]. Despite its evident benefits [95–97] to teaching and learning, simulation training in general aviation training often is not exploited to its fullest potential. Alongside this, simply accumulating the regulatory minimum number of flight hours should not be seen as the only measure of true competence. Thus, to evolve beyond the traditional hour-based in-aircraft training requirements, a re-evaluation of training time distribution between in-aircraft and FSTD training is essential. This re-evaluation should prioritize maximizing the use of FSTDs. Although real aircraft flying remains the gold standard for pilot training and licensing, directly replacing an hour of in-aircraft training with an hour of FSTD training may not be a suitable approach. The potential substitution of FSTD training for in-aircraft flight training within the current PPL and CPL regulatory requirements needs thorough examination. For instance, it must be determined whether an hour of FSTD training could equate to an hour of in-aircraft training or if multiple hours of FSTD training are needed to replace a single hour of in-aircraft training. Finding the optimal balance between FSTD and in-aircraft training will ensure the full advantages of simulation training are realized without compromising on training quality or safety.

Electric aircraft and SAF have also been highlighted as means to mitigate CO₂ emissions. However, the widespread adoption of these technologies demands interdisciplinary collaboration, encompassing a diverse range of stakeholders, including government, industry, research institutions, and the public. While their implementation seems promising, further research is essential to address any associated challenges.

2.7 Conclusion and Policy Implications

In light of the rapid growth in the global aviation sector and the associated surge in CO₂ emissions, achieving sustainability remains a paramount challenge. The unanimous goal across international aviation agencies to reach net-zero emissions by 2050 highlights the urgency of the situation. Central to this

endeavor is the critical understanding and reduction of CO₂ emissions from all facets of the sector. The findings of this study underscore the urgent need for policy interventions to mitigate the environmental impact of pilot training in Canada's general aviation sector. Our estimation that each hour of ab initio flight training emits about 70.4 kg of CO₂, cumulating to approximately 30,000 tonnes annually, highlights a potential area for emissions reduction within the aviation sector. This revelation underscores the necessity of adopting measures aimed at reducing emissions, thereby contributing to the global aviation community's objective of attaining net-zero emissions by 2050. Policy implications derived from these findings suggest a multi-faceted approach towards sustainability. Firstly, there is a strong case for regulatory support in favor of flight simulation training devices (FSTDs). By recognizing additional FSTD hours towards licensing requirements, actual flight hours and emissions could be reduced. Secondly, the transition to electric aircraft for training purposes emerges as a viable path to decarbonization, with policy mechanisms such as tax incentives and subsidies proposed to hasten their adoption. Similarly, the promotion of SAF could offer immediate reductions in carbon emissions, albeit its current limited adoption due to cost and availability challenges necessitates supportive policies for development and distribution. Additionally, the establishment of a comprehensive emissions reporting policy for flight schools would foster transparency and encourage the adoption of greener practices, potentially supported by a public registry of emissions data. Finally, achieving sustainable aviation training mandates a collaborative effort among all stakeholders, including regulators, training institutions, and aircraft manufacturers, to share innovations and best practices. In essence, while the study primarily zeroes in on Canada's aviation training emissions, its findings and recommendations hold broader implications, advocating for a global shift towards more sustainable pilot training practices. This aligns with the wider aviation industry's sustainability goals, emphasizing that the sector's growth should not compromise environmental integrity. Moving forward, a concerted effort involving innovation, commitment, and collaboration is paramount to actualizing these sustainable practices across the aviation ecosystem.

Chapter 3 (Study 2)

Exploring Perceptions of Pilot Licensing and Training Standards: A Survey of Canadian Student and Licensed Pilots

3.1 Introduction

In the realm of civil aviation, safety stands as the foremost priority, with human factors acknowledged as essential elements in its preservation. Research indicates that human factors are implicated in approximately 75% of civil aviation accidents, encompassing issues like loss of situational awareness, poor decision making, deviations from standard procedures, incapacitation, and communication failures [98–103].

An analysis of data from the Transportation Safety Board of Canada reveals that between 2013 and 2023, Canadian-registered aircraft were involved in 2,093 accidents, defined as severe occurrences with significant harm. Of these, 1,455 were related to general aviation, averaging 132 accidents annually [104]. These statistics underscore the ongoing risks and highlight the need for continual improvements in general aviation safety practices. For clarification, general aviation encompasses all private and non-commercial aviation activities, excluding regular airline flights and fee-based cargo transport services [105]. This includes recreational flying, pilot training, agricultural aviation, law enforcement operations, medical air transport, land surveying, and various unscheduled commercial activities. This classification highlights a broader segment of aviation that extends beyond commercial airlines and cargo transport, capturing the essence of private and non-commercial aviation endeavors.

Pilot training in Canada is governed by strict practices and standards to ensure safety, all under the oversight of Transport Canada [106]. Despite these rigorous standards, the industry faces challenges, including meeting the increasing demand for pilots and adapting to rapid technological advancements. The COVID-19 pandemic intensified Canada's existing pilot shortage, leading to early retirements amid industry challenges [107]. In 2018, the Canadian Council for Aviation and Aerospace (CCAA) projected a need for an additional 7,300 commercial pilots by 2025 to meet growing demand, specifically emphasizing the requirement for those holding a Commercial Pilot License (CPL) [108]. This projection underscores the increasing necessity for pilots with advanced credentials, including the Airline Transport Pilot License (ATPL). Within the civil aviation sector in Canada, CPL holders frequently seek to advance to ATPL certification, further amplifying the demand for these higher-level qualifications. The current shortage of qualified pilots has enabled recent flight school graduates to secure positions with major carriers earlier in their careers, emphasizing the urgency to elevate pilot training and licensing standards to improve the quality of new pilots and address future industry needs [109]. Meanwhile, advancements in computer and

information technologies, including simulators, virtual reality (VR), and artificial intelligence (AI), have significantly evolved [110–115]. Despite these technological leaps, their integration into pilot training across Canada remains limited, maintaining traditional practices for decades [116]. Recognizing such issues, the forty-first assembly of the International Civil Aviation Organization (ICAO) emphasized the need for agility and innovation in pilot training [117]. It highlighted the importance of optimizing training programs to improve safety and operational efficiency, reflecting a global consensus on the need to modernize pilot training and licensing not just for commercial air transport sub-sector, but also for general aviation. This includes adapting to technological advancements and evolving industry needs to ensure pilots are prepared for the demands of modern aviation.

Pilot licensing in Canada is a staged process, with the most common training pathway starting with the Private Pilot License (PPL) and subsequently progressing to more advanced certifications. The PPL allows individuals to fly single-engine aircraft for personal use. For those aiming to pursue a career in civil aviation, the next step is the CPL, which permits employment as a pilot, including flying single-pilot aircraft and co-piloting multi-crew aircraft with additional ratings. After acquiring a CPL and meeting the extensive training requirements for the ATPL, individuals can take the ATPL exams and flight test. The ATPL, the highest civilian pilot license, qualifies pilots to serve as captains or pilots-in-command of multi-crew aircraft for both regulated and private airlines. However, possessing an ATPL alone is often insufficient for airline employment, as additional qualifications and employer-specific requirements may apply. Regardless of the type of license, the pilot licensing and training process in Canada relies on a series of conventional training requirements, with long-established hours-based training practices being a key component [118]. To obtain a pilot license, student pilots must complete ground instruction and accumulate the necessary flight training hours, with advanced level licenses demanding broader training. However, reliance on flight hours as the primary competency measure has its limitations, as pilot proficiency can significantly vary among individuals with identical hours logged [109]. This discrepancy underscores the need for a more nuanced competency evaluation beyond mere flight hours. Internationally, this issue has also been recognized for several years, prompting certain civil aviation authorities (CAA) to adopt competency and evidence-based flight training methodologies. For example, the European Aviation Safety Agency (EASA) has implemented Competency-Based Training and Assessment (CBTA) and Evidence-based Training (EBT) across its member states [119,120]. Similarly, the Civil Aviation Administration of China (CAAC) has also embraced a hybrid approach of CBTA and EBT, leading many Chinese airlines to follow suit [121,122]. However, the adoption of these methods has been primarily within the commercial air transport sector, with limited application in general aviation pilot training. Moreover, in some instances, the focus of their implementation has been quite narrow, concentrating solely on the development and assessment of specific pilot competencies. To aid CBTA and EBT adoption, detailed guidance materials [123–125] have

also been made available to CAAs, Operators (AOC), and Approved Training Organizations (ATO) by international aviation agencies such as ICAO and International Air Transport Association (IATA), facilitating a standardized approach across civil aviation industry.

Furthermore, the flight test assessment process in Canada, irrespective of the license type being pursued, combines objective metrics with subjective judgments by examiners, introducing variability in the evaluation [126]. Adding to these challenges, the integration of flight simulation training devices (FSTDs) in typical ab initio training programs [127] across flight schools in Canada presents regulatory, technological, and pedagogical hurdles, impacting the effectiveness of training outcomes [109,128,129].

Considering the reported air transportation accidents involving Canadian-registered aircraft, the noticeable lag in adopting modern technologies, the guidance provided by ICAO, and the evident inadequacies in pilot training and licensing standards, there is an imperative need to explore the limitations of the prevailing regulatory and educational framework. Driven by this necessity, this study seeks to investigate the perspectives of student and licensed pilots, on the existing practices of airplane pilot licensing and training, aiming to pinpoint opportunities for enhancement. However, within the scope of pilot licensing and training, this study specifically focuses on general aviation pilot training within the civil aviation sector. Through this analysis, the goal is to uncover actionable insights that can address the current shortcomings and align general aviation pilot training and licensing more closely with the evolving demands of aviation safety and technological progress. Accordingly, our objective is to explore the limitations of Canada's existing general aviation pilot training and licensing practices and to uncover new opportunities that can enhance pilot training, offering valuable insights and actionable recommendations. Specifically, the two research questions we will explore are as follows: 1) Do student and licensed pilots regard accumulated flying hours as a reliable indicator of pilot competence? 2) Do student and licensed pilots perceive current pilot training practices and standards as adequately addressing pilots' educational and practical needs, ensuring key instructional and assessment elements are met?

It is important to emphasize that including student pilots in this study was a deliberate decision to capture the perspectives of individuals actively engaged in training. Their feedback can be vital for assessing the relevance of current practices and understanding how effectively these could prepare them for real-world scenarios, directly supporting our study's objective of investigating the perspectives on the existing practices from multiple viewpoints.

3.2 Literature review

3.2.1 Literature Review Method

3.2.1.1 Scoping Review Process and Methodology

This scoping review adheres to the PRISMA-ScR framework [130], ensuring transparency and rigorous methodology to thoroughly explore research questions and minimize bias. We followed a six-step protocol: 1) conducted a comprehensive literature search across various academic databases aligned with our research objectives; 2) screened titles and abstracts for eligibility; 3) reviewed full texts to finalize inclusions based on specific criteria; 4) extracted relevant data from the selected studies; 5) summarized the findings. Subsequent sections will detail our research sources, approach, screening criteria, and the process used to review and select studies for inclusion.

3.2.1.2 Research Sources

The search for relevant literature was conducted across four key databases: Google Scholar, BASE, CORE, and WorldCat. Google Scholar provided extensive access to freely available academic papers, including interdisciplinary studies. BASE contributed a significant volume of specialized articles, enriching the content diversity. CORE, which compiled open-access research from multiple repositories, served as a valuable resource for accessing diverse and comprehensive academic works. WorldCat, a global catalog of library collections, offered a wide array of sources, ranging from academic journals to contemporary discussions, enabling access to content from libraries worldwide. Collectively, these databases facilitated a comprehensive and focused review of literature across various disciplines, directly relevant to our study's objectives.

3.2.1.3 Research Approach

The literature search was conducted using a set of well-defined search keywords and a broad array of corresponding synonyms to ensure a thorough retrieval of relevant publications. The primary keywords were "pilot training standards," "perceptions of pilot training by student or licensed Pilots," "challenges in civil aviation education and training," "pilot training limitations," "shortcomings in pilot licensing," and "regulatory shortfalls in pilot training." To expand the search, synonyms such as "aviation training guidelines," "opinions on flight training from student or licensed Pilots," "obstacles in pilot training," "limitations in flight training programs," "deficiencies in pilot certification," and "regulation gaps in aviation training" were utilized. This comprehensive approach ensured a detailed exploration of literature across various aspects of pilot training and licensing.

3.2.1.4 Screening Criteria

This scoping review primarily concentrated on the current literature on pilot training standards and practices, perspectives of student or licensed pilots on pilot licensing and training practices, and regulatory challenges within pilot training education and training, aiming to provide a comprehensive overview of these critical areas. To ensure a focused and relevant selection of publications for this review, specific inclusion and exclusion criteria were established. The inclusion criteria required that only peer-reviewed journal articles or published conference papers from pertinent academic disciplines such as Aviation and Aerospace Studies, Education and Training, Safety Science, Human Factors and Ergonomics, and Management and Organizational Studies be considered. These publications must specifically cater to 'airplane' pilot training and licensing, be published within the last 12 years (2011-2023), and are written in English to ensure that the data is both current and accessible. The publications needed to employ empirical research methodologies involving primary data from student or licensed pilots. Accepted research methodologies encompassed structured or semi-structured surveys, in-depth individual interviews, or moderated focus group discussions or reviews, ensuring a thorough data collection. Moreover, these publications needed to perform a comprehensive analysis of the collected data, clearly report findings with appropriate statistical or thematic analysis methods and discuss study limitations. The selection process for participants had to be explicitly defined, and data collection needed to utilize reliable and validated tools. If new tools were developed, their validation processes were required to be thoroughly documented. Ethical standards were pivotal; studies had to have obtained necessary approvals, ensuring informed consent, confidentiality, and participant safety. While the geographical focus area was on Canada, the geographical scope was expanded internationally, including countries and regions like the U.S and Europe, due to similarities in pilot training and licensing practices. In addition to peer-reviewed journal articles and published conference papers, relevant reports and guidance materials from international aviation agencies (e.g., ICAO, IATA) were also included to enrich the context and applicability of the review findings. Conversely, the exclusion criteria ruled out non-peer-reviewed materials such as book chapters, online articles, magazines, and studies not written in English. Articles primarily based on literature reviews were typically excluded unless they served as critical supporting information through seminal works or comprehensive reviews that delivered unique theoretical insights or a thorough contextual understanding. This strategy ensured that these reviews augmented the narrative without becoming the empirical foundation of our research conclusions. Studies conducted in experimental laboratories were excluded to favor research in natural, operational settings that more accurately reflected real-world pilot training environments. In addition to the Inclusion & Exclusion criteria screening, an applicability review ensured that only publications closely related to the core research questions concerning views of student or licensed

pilots on the reliability of accumulated flying hours as an indicator of pilot competence or the adequacy of current training practices were included, ensuring the findings were relevant and focused.

3.2.1.5 Screening Process

Screening Process: The screening process was conducted using Covidence as the primary tool to enhance efficiency. Initially, all search results ($n = 1273$) from various databases were uploaded to Covidence, leading to the automated removal of duplicates ($n = 297$). The subsequent phase involved title and abstract reviews where a significant number of publications ($n = 762$) were excluded for not aligning with the established research focus. A more detailed full-text screening of the remaining 214 publications resulted in the exclusion of an additional 167 publications that failed to meet the predefined eligibility criteria. The rigorous selection criteria narrowed to 47 potentially relevant publications. Each of these was further scrutinized for its direct relevance to the core research questions. This in-depth evaluation, conducted by two independent researchers, led to the final inclusion of 13 publications deemed most pertinent.

The excluded publications were organized into distinctive groups, each providing valuable insights yet not addressing the core research questions regarding the reliability of accumulated flying hours as indicators of pilot competence or the adequacy of current training practices. We've included a few examples for context: In the "Technological Innovations and Tools" group, [131] explored how virtual reality simulations can enhance learning efficiency for ab initio pilot training, and [132] assessed the role of VR training devices by comparing them with PC-based simulators, noting their effectiveness in improving pilot performance, however neither directly addressed our core questions regarding the perceptions of student or licensed pilots on flying hours being competency measure or adequacy of current training practices. In the "Training Effectiveness and Methods" group, [133] focused on fatigue management strategies in pilot training, emphasizing pilot health over training standards, [134] evaluated assessment tools for improving knowledge retention and decision-making, and [135] provided insights into various teaching methods, but all these publications lacked direct evaluations of the adequacy of current training effectiveness. The "Regulatory Impact and Compliance" group featured [136] and [137], who analyzed regulatory and economic impacts of changes on training costs and investigated how safety culture across flight training organizations influences training outcomes, but neither study assessed training adequacy or pilot competence directly. Finally, the "Educational Strategies and Perspectives" group included [138], who surveyed flight instructors on effective teaching methods, highlighting instructional discrepancies but not connecting these to views of student or licensed pilots on pilot competence or training practices. [139] discussed the low female representation in pilot training, and [140] explored educational frameworks in aviation training. Both provided valuable insights but did not directly evaluate their impact on training effectiveness or address core research questions about training practices or standards.

Figure 3 presents a PRISMA-ScR flowchart, detailing the systematic procedure for identifying, screening, and reviewing publications for inclusion in this scoping review. The findings and characteristics of the included publications were synthesized and are presented in the next section.

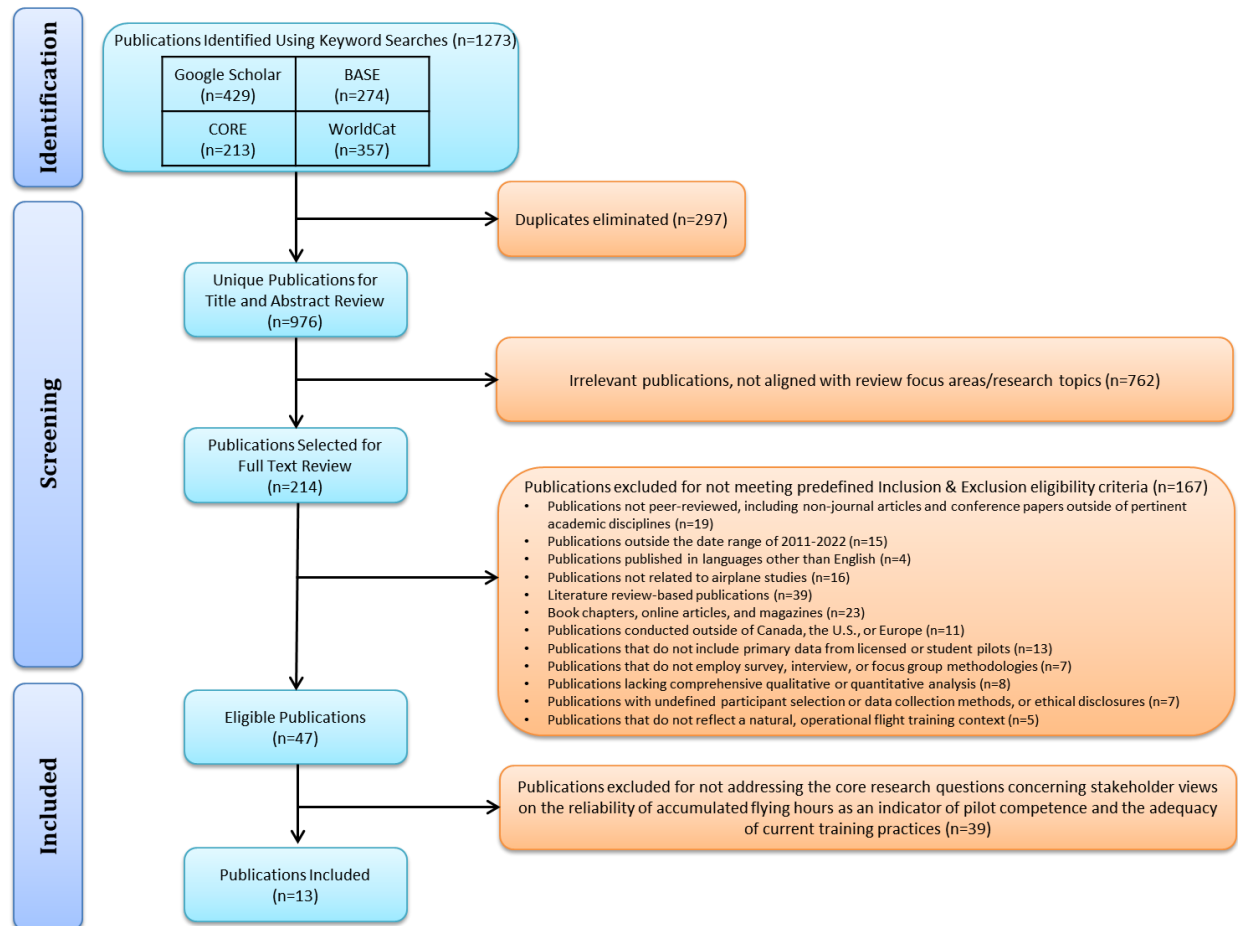


Figure 3: Selection of studies using PRISMA flowchart

3.2.2 Literature Review Results

Building on the systematic identification and selection process detailed earlier, this section delves into a detailed synthesis of the findings and characteristics of the thirteen publications that met our criteria for inclusion.

Davis's study, involving interviews and flight simulator evaluations with 10 seasoned non-professional pilots in Canada, found that the country's educational and regulatory standards fall short in ensuring operational proficiency [141]. The study suggested adopting improved training standards, stricter rules, and fostering a culture of ongoing skill enhancement. A key issue identified was Transport Canada's relaxed approach to enforcing rules, creating an environment where pilots might ignore regulations without

consequences. The study also noted differences in training rigor between professional and non-professional pilots, particularly PPL holders, suggesting their recurrent training might not adequately maintain proficiency. The flight simulator evaluations revealed a gap between pilots' training and their ability to handle emergency situations. However, the study's focus on a specific group of PPL holders from British Columbia, its small sample size, and age skew (average participant age: 54), along with participants' infrequent flying practices, limit its broader applicability and indicate that its findings should be interpreted with caution.

Kearns and Sutton explored the belief that all flying hours on similar aircraft are equally valuable by focusing on non-technical skill development through real-world flying experiences [142]. Their study utilized a self-report survey to gather narrative descriptions and involved narratives from 130 Canadian general aviation pilots about their experiences, including challenges and the use of non-technical skills. The findings indicated that flight hours alone might not fully assess non-technical skill progression due to variations in pilots' operational backgrounds. However, the study's limitations include participants reporting only one significant event, which might not capture their complete skill development, and a broad categorization of errors and skills, missing nuanced differences in operations. The research suggests the need for future studies to more objectively evaluate pilot experience across diverse flight operations to better understand skill development.

Fursenko's study analyzed Canada's pilot training system, focusing on regulatory requirements and training methods to identify modernization opportunities [143]. It pointed out the need for modernization, emphasizing the use of outdated equipment and resources in flight schools. It recommended updating training materials, adopting advanced technologies such as flight simulators, and shifting towards competency-based training for greater efficiency and lower costs. However, the study was limited to secondary sources and lacked direct pilot feedback and quantitative outcome assessments, indicating that future research should include interviews or surveys for a comprehensive evaluation.

Efthymiou et al.'s study investigated why over half of the CPL applicants in Europe fail airline assessments despite training at European Aviation Safety Agency (EASA)-accredited flight schools [144]. Conducting interviews with 12 industry professionals, including students and instructors, the research pinpointed deficiencies in technical knowledge, preparation, communication, and leadership as significant factors. However, the study had limitations due to its small and specific participant sample of only two students, one instructor, and one examiner, which might not fully capture a comprehensive understanding of training effectiveness.

Majumdar and Marais surveyed 128 U.S. pilots, uncovering training deficiencies in handling in-flight loss of control (LOC) incidents, particularly in spins and spirals [145]. It suggested the need to improve

training with specific focus on LOC recognition and recovery techniques, aiming to better equip pilots for such emergencies. Though providing valuable insights into LOC recovery, the study's specialized scope limits its relevance to other inflight emergencies.

Casner's study in the U.S. assessed the effectiveness of ATPL training in preparing pilots for unusual in-flight situations [146]. With 18 experienced U.S. airline pilots and using a simulator for three unique flight scenarios, the study found that traditional training methods, reliant on memorization, fell short in unexpected scenarios. Pilots were adept at handling familiar situations but struggled with novel and abnormal events, underscoring a critical gap in training that does not fully prepare them for real-world flying's unpredictability. The recommendation is for enhancing training to focus on recognizing and managing unusual flight scenarios. However, the study's findings, focused on ATPL training, may not apply universally across different pilot licenses, potentially affecting the study's broader relevance.

Hale and Breaux's study explored the instructional challenges flight instructors face, noting that safety concerns can delay in-flight teaching and slow error correction [147]. It highlighted how students' focus on flying limits in-flight instruction opportunities. To improve training, the study recommends low-fidelity, scenario-based training and detailed performance measures. However, the study's conclusions are based more on theoretical analysis than on empirical data or direct instructor feedback.

Kolmos's study critiques the prevailing 'one size fits all' approach in pilot training, emphasizing its challenges for older pilots who learn differently from younger peers, especially when adapting to advanced cockpit technologies [148]. It advocates for age-specific training methods to ensure a smooth transition to modern cockpits. However, the study's reliance on literature and theoretical frameworks might not accurately represent the practical experiences of pilots undergoing this transition.

Guidance materials from ICAO and IATA provide valuable frameworks for enhancing pilot training and assessment, although their applicability to general aviation is limited. The ICAO's "Manual of Evidence-based Training (EBT)" offers detailed guidelines to civil aviation authorities, operators, and training organizations for the ongoing assessment and training of pilots utilizing FSTDs [125]. The manual promotes a shift from traditional, scenario-based training to a competency-based approach, focusing on assessing and developing essential competencies for modern aviation safety. This EBT framework leverages data from accident and incident reports, flight data analysis, and safety studies to ensure training is relevant to actual threats and errors in flight operations. Despite its comprehensive guidance on developing training programs and evaluating flight crew performance, the manual primarily caters to commercial air transport. The manual's implementation in general aviation could be hindered by the complexity of necessary data collection and analysis, which may be impractical on a smaller scale due to limited resources. Over the past decade, IATA has worked to consolidate data from various sources such

as flight data analysis, safety reports, and pilot surveys to identify improvement areas [149]. This collaboration led to the creation of the "Evidence-based Training Implementation Guide" by IATA [124]. This guide integrated the latest regulatory and industry best practices, providing revised guidelines on how to implement the provisions of ICAO's "Manual of Evidence-Based Training" [125] and the applicable sections from ICAO's "Procedures for Air Navigation Services – Training" [150]. It provides a structured approach for implementing EBT programs to enhance pilot competencies through a data-driven process. It emphasizes continuous data refinement to address significant operational risks. However, the extensive data requirements and advanced analytical tools needed for EBT are often out of reach for general aviation operators, who typically have fewer resources and a less formalized training structure. Additionally, IATA's "Competency Assessment and Evaluation for Pilots, Instructors, and Evaluators" offers a thorough framework for competency-based training and assessment (CBTA) [123]. This details assessment processes and methods aligned with industry best practices, aiming to comprehensively evaluate pilot performance and instructor effectiveness. Yet, its effectiveness in general aviation is limited due to the sector's diverse and decentralized nature. The rigorous data requirements and structured assessment processes, ideal for larger commercial settings, pose a challenge for general aviation entities, which might struggle with these demands due to their smaller scale and less structured environments. As well, the manual's focus on commercial aviation scenarios limits its relevance to the varied nature of general aviation operations.

Our literature review indicates that pilot training and licensing research in Canada, particularly in the general aviation sub-sector, is significantly under-researched. While some publications identify gaps in current practices and methodologies, many critical areas remain unexplored. International research also highlights additional gaps, presenting opportunities for future investigations. Previous publications also had small sample sizes, focused on specific training aspects, or relied on theoretical discussions without direct data collection from the student pilots or pilot workforce. Publications from international agencies provided detailed frameworks and practical guidelines, such as CBTA and EBT methodologies, that can enable implementation of effective pilot training and assessment programs. However, these are merely guidelines, not enforceable regulations. In practice, general aviation in Canada predominantly adheres to traditional and hour-based methods, and the level of assessment currently in place is not detailed enough to satisfy the criteria set forth by these CBTA and EBT methodologies [116,118,151–153], highlighting a significant gap. Furthermore, it also remains uncertain whether student pilots at the ab initio or grassroots level will adopt these methodologies. Assessments at the end-user level are necessary to determine the acceptance and feasibility of these approaches among new pilots. While CBTA and EBT methodologies outlined in these publications could be effective, these methodologies primarily focus on commercial civil aviation, suggesting that adaptations are necessary when applying these guidelines to general aviation. This will ensure that the unique challenges and requirements of general aviation are adequately addressed.

To address these research gaps, our study will ensure diverse representation across age, experience levels, and operational backgrounds by engaging directly with student pilots, and licensed pilots from both general and commercial aviation sub-sectors. Although our focus is on general aviation, including pilots from the commercial sub-sector provides a comprehensive range of perspectives and experiences, offering valuable insights into best practices and common challenges across different aviation contexts. Additionally, the interplay between general and commercial aviation practices can reveal areas where general aviation training could benefit from commercial sector innovations and best practices. This approach will enable us to comprehensively assess current pilot training practices, highlight underexplored areas, and develop well-informed, evidence-based recommendations for general aviation pilot training and licensing standards in Canada. The insights derived will aim to enhance the safety, efficiency, and technological integration of pilot training programs, aligning them with the practical and evolving demands of the civil aviation industry.

3.3 Method

3.3.1 Research Instrument

3.3.1.1 Survey Design and Scope Overview

An internet-based survey was developed to collect self-reported perceptions from both student and licensed pilots, aimed at assessing the current general aviation pilot training standards and practices, and to solicit feedback on existing limitations and potential areas for improvement. It comprised 10 carefully curated questions, balanced between quantitative and qualitative inquiries. Five questions used a 5-level Likert scale, grounded in self-perceived reporting of established training practices to gain a broader understanding of training experiences. The remaining five questions were open-ended, designed to elicit comprehensive insights into the limitations of the training and assessment practices along with their potential opportunities for improvement. These open-ended questions were included to allow for a richer, more detailed exploration of the subject, which standardized scales may not fully capture. This mixed-methods approach was adopted to enable a holistic assessment, combining structured data from Likert questions with in-depth qualitative feedback from open-ended questions. Demographic data, including age, gender, education, pilot licenses, training locations, flying experience, ratings, and medical categories, were also collected for each participant. It is important to note that this survey did not aim to evaluate training outcomes or validate current methods. Moreover, it did not collect any objective data, such as behavioral, physiological, and other subjective constructs like situational awareness or mental workload, nor did it involve gathering data from experiments conducted in controlled settings. Instead, it focused on gathering pilots' subjective opinions about their training experiences. By assessing their perspectives and satisfaction, this survey

sought to capture insights into the perceived effectiveness and value of current training practices without attempting to validate their efficacy. Therefore, this study represents a perception-based assessment rather than a validation of training efficacy.

Additionally, the survey was strategically crafted to capture broad insights into general aviation training practices without categorizing inquiries by different license certifications or ratings. This approach was intended to provide an overarching understanding of the training landscape, highlighting themes and commonalities across all areas of general aviation pilot training. By eschewing segmentation by license type or rating, the design aimed to prompt survey participants to consider their entire training journey, thus allowing for a broader collection of experiences and perceptions. This approach was also designed to circumvent issues related to variability from specialized certifications and to mitigate bias that might arise if participants felt their experiences were narrowly defined by specific certification milestones. Consequently, the survey was specifically designed to enable a thorough exploration of training and assessment practices within general aviation, aligning with the study's objective to assess the overall effectiveness and satisfaction with these practices. The 10 survey questions are shown in the Table 2.

Table 4. Survey questions to assess perceptions on general aviation training practices

Where applicable, rate statements using a 5-point Likert scale ranging from 1 ('Strongly Disagree') to 5 ('Strongly Agree'), with 2 indicating 'Disagree,' 3 'Neither Agree nor Disagree,' and 4 'Agree.' Provide descriptive responses for inquiries that do not fit this format. 1. Flight time or total flight experience (accumulated flying hours) is a reasonable method to quantify pilot competence. 2. High-quality flight training could result in improved acquisition of the necessary knowledge, skills, and abilities to fly an aeroplane versus flight training that focuses simply on the number of hours flown. 3. From an instructional and learning context with respect to current flight training standards for both dual instruction training and solo flying, there exist limitations that potentially impact the training outcomes. 4. Briefly outline those limitations (if any). 5. Briefly outline any opportunities for improvement to address the limitations identified previously. 6. Aside from limitations identified previously (if any), current flight training standards adequately serve training needs and ensure satisfactory proficiency in technical and non-technical flying competencies. 7. Briefly outline areas of improvement (if applicable). 8. Flight test assessment and evaluation are conducted objectively, with a minimal degree of subjectivity. 9. Briefly outline any assessment-based limitations across current flight training standards (if any). 10. Briefly outline any opportunities for improvement to address the limitations identified previously.
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3.3.1.2 Survey Design Logic

The theoretical basis for utilizing the survey as a research instrument, along with the design of the survey questions including demographic data collection elements, was rooted in previously published literature

[142,145,154–165] with validated frameworks tailored to civil aviation research. These questions were developed following a thorough review of existing literature and well-established theories, thereby confirming the appropriateness of the survey instrument and its design for the intended research. Given the exploratory nature and qualitative focus of half the survey questions, and considering that the remaining questions are single-item and do not measure any specific construct, traditional statistical reliability testing was deemed inapplicable [166–169]. Instead, the survey underwent expert review and pre-testing conducted by pilot training experts (Certified Flight Instructors) and a mix of student and licensed pilots. This rigorous process enhanced the questions' clarity, relevance, and neutrality, ensuring they remained unbiased and well-aligned with the research objectives.

3.3.1.3 Statistical Credibility of Five-Question Likert Scale Data

This survey includes five Likert scale questions, which may lead some to question the statistical credibility of using only a small number of Likert scale questions. However, numerous studies [170–177] published in the literature have demonstrated the feasibility of conducting credible research with a small number of Likert scale questions. These studies, across various research contexts and disciplines, including aviation-based research, confirm that robust statistical analyses can be effectively conducted with limited Likert scale data, provided that the analytical methods are carefully selected to suit the specific context of the study and that the data undergoes necessary validation processes. This supports the viability of our approach, ensuring that the survey results are both statistically credible and methodologically sound.

3.3.2 Procedure

The survey, developed on the Qualtrics platform, was available online for about four months. It was advertised to student, and licensed pilots in general and commercial aviation across Canada, through flight schools, aviation organizations, and social media. The survey, ensuring confidentiality, required participants to consent before proceeding, was voluntary and anonymous. Utilizing snowball sampling, participants were encouraged to share the survey, broadening the participant base. This study has been reviewed and received ethics clearance through University of Waterloo Research Ethics Board (#45717).

After excluding missing or incomplete entries, the survey collected 206 valid responses. The numerical data underwent a cleaning process for statistical analysis, which involved fixing typographical errors and standardizing text variables into numerical values to ensure data integrity and reliability. For open-ended questions, irrelevant content was removed, response formats and language were standardized, and duplicates were eliminated. Data was analyzed using IBM SPSS® 29.

3.4 Results

3.4.1 Demographic Insights

The survey garnered responses from 206 participants, consisting of both student and licensed pilots. Figure 4 depicts the percentage distribution between these groups, as well as the variety of license types held by the licensed pilots, including Private Pilot License (PPL), Commercial Pilot License (CPL), Integrated Airline Transport Pilot License (IATPL), and Airline Transport Pilot License (ATPL). Additionally, Figure 5 presents the gender distribution and educational levels of the participants. Age analysis of participants showed an average age of 29.53 years, a median of 24 years, and a standard deviation of 12.30, indicating a wide age range from 17 to 71 years.

Flying experience analysis spanned from beginners with zero flight hours to veterans with over 40 years and up to 30,000 hours in aviation, averaging 1,890 hours but with a high variability (standard deviation of 3,867 hours). This range highlighted the varied proficiency levels, from modest to well-established aviation careers. Additionally, pilots' training backgrounds were diverse, with majority trained in Canada, but some also received education or ratings from countries like Vietnam, France, the USA, and the UK. Regarding medical fitness, the majority (192) of participants met the high standard of Category 1, whereas a smaller group (14) qualified for Category 3.

The survey data revealed varied ratings associations with pilot license holders. PPL holders predominantly had Night Ratings, with 25 pilots accredited; however, 30 lacked additional ratings. In contrast, CPL holders displayed a wider array of qualifications beyond Night Ratings, with the majority also possessing Multi-Engine and Instrument Ratings, alongside Instructor, Seaplane, and specific Type Ratings for aircraft such as Boeing 737-800 and Airbus A32F. IATPL holders mainly had Multi-Engine, Instrument, and Night Ratings, with a few also holding Seaplane and specialized Type Ratings. ATPL holders exhibited a comprehensive skill set, universally holding Multi-Engine and Instrument Ratings, and many also had Seaplane, Night, Instructor, and Type Ratings for various aircraft, including Boeing, Bombardier, and specialized models like the DC3T.

The average duration of survey participants as pilots since obtaining their first license was 8.2 years, with a standard deviation of 10.8 years. Given that the Flight Training Manual (TP 1102E), Flight Instructor Guide - Aeroplane (TP 975E), Pilot Decision Making (PDM) Manual (TP 13897), and Instrument Procedures Manual (TP 2076E) were last published in 2004 and 1997 respectively [116,151–153], it is evident that these resources, which are integral to general aviation training in Canada, have not been updated in two decades. These manuals cover essential aspects such as theoretical knowledge and practical instructions for student pilots, guidelines and best practices for instructors, human factors, decision-making

processes critical for safe flight operations, and detailed procedures for instrument flight rule (IFR) operations. Therefore, it was reasonable to conclude that the training perceptions provided by survey participants align with current Canadian civil aviation standards. This alignment confirms that the survey insights accurately reflect ongoing pilot training practices in Canada, despite the manuals' lack of recent updates.

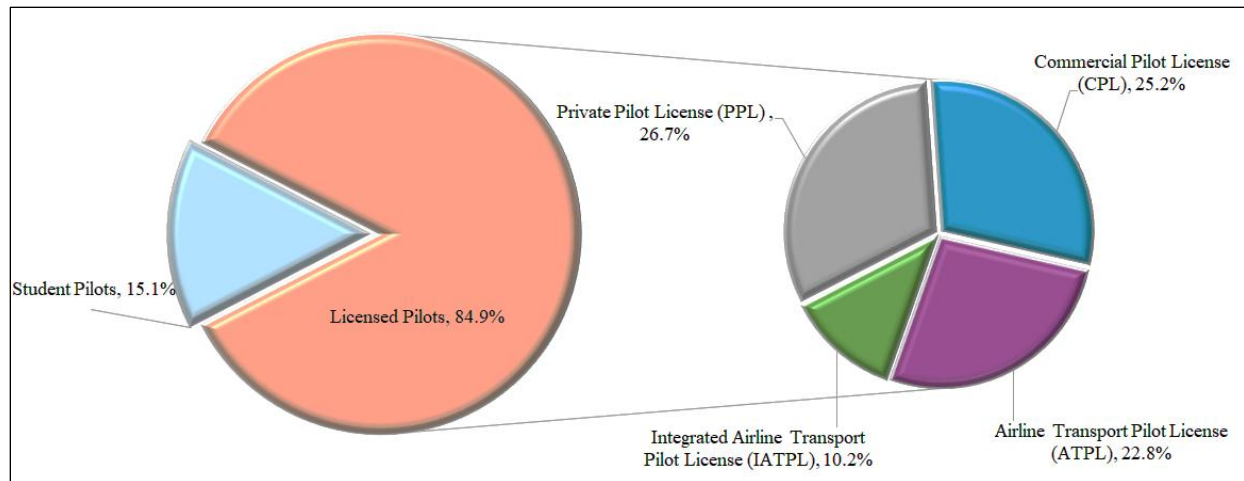


Figure 4: Percentage distribution of student and licensed pilots, with breakdown by license types

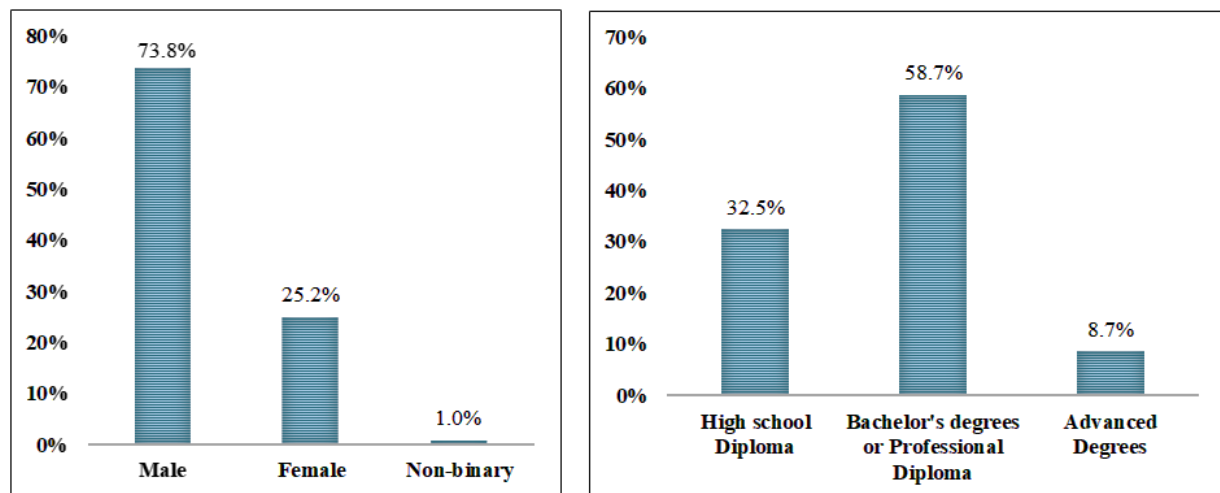


Figure 5: Distribution of gender and educational levels among survey participants

3.4.2 Quantitative Findings

Statistical techniques, both descriptive and inferential, were utilized to analyze the perceptions of student and licensed pilots based on their responses to Likert scale questions in the survey. Participants rated their level of agreement on a 5-point Likert scale, with the following values: 1 for 'Strongly disagree,' 2 for 'Disagree,' 3 for 'Neither agree nor disagree,' 4 for 'Agree,' and 5 for 'Strongly agree.' The study analyzed data from a diverse participant pool, including student pilots and various licensed (PPL, CPL, IATPL,

ATPL) pilots, to identify differences in opinions among these groups. It also explored gender differences within these groups. It should be noted that the primary research questions centered on perceptions among student pilots and licensed pilots with different license types, including PPL, CPL, IATPL, and ATPL, without initially considering demographic variables such as gender. However, as a secondary aspect of the research, the effect of gender on responses to each Likert scale question was explored. This was undertaken to highlight specific barriers faced by underrepresented genders [178,179] in the predominantly male civil aviation industry. Unfortunately, the data collected did not include sufficient combinations of participant group and gender to reliably analyze their interaction effects. Therefore, the analysis treated participant group and gender separately to ensure a robust analysis within the constraints of the available data.

Statistical analysis treated participants' level of agreement or disagreement (Likert scale rating) as the dependent variable, reflecting their perceptions. The different participant groups, including student pilots and various licensed pilots (PPL, CPL, IATPL, ATPL), were treated as the independent variable to evaluate how these groups might influence the responses. There were no covariates or control variables.

The Shapiro-Wilk test showed a significant deviation from normal distribution (p -values <0.001) in the response data for each Likert question. Research by [180,181] underscores the importance of sample size in accurately conducting transformations to normalize data, recommending a minimum of 1000 samples for reliable parametric estimation in non-normal distributions. Given that our survey's sample size was only 206, the expected transformation effects were likely not sufficiently pronounced; thus, data transformation was not pursued.

Given the non-normal distribution of the data, [182–184] recommend employing nonparametric methods for statistical analysis. Accordingly, we implemented nonparametric techniques that do not assume normal distribution. We used the independent sample Kruskal-Wallis test to analyze responses to each Likert scale question. For more detailed group-specific comparisons and gender-based analysis within the groups, post-hoc analyses using Dunn's multiple comparisons test or the Mann-Whitney U test were conducted.

3.4.2.1 Pilot Perspectives on Flight Time as a Competence Measure

Regarding the use of flight time or total flight experience as a criterion for assessing pilot competence, the overall mean score was 2.70, hinting at a slight disagreement but mostly neutral stance, with a standard deviation of 1.21 indicating diverse views. A closer look at the responses by participant groups showed a discernible trend. Pilots with advanced certifications (ATPL: mean 2.17, SD 1.19; IATPL: mean 2.19, SD 0.98; CPL: mean 2.63, SD 0.97) generally leaned more towards disagreement, expressing skepticism about a direct link between flight time and competence. In contrast, less experienced pilots, particularly PPL holders (mean: 2.96, SD: 1.23), had views almost aligning with neutrality, albeit slightly skewed towards

disagreement. Conversely, student pilots (mean: 3.48, SD: 1.23) appeared to regard flight time as an essential factor in developing competence, as their average score veered more towards agreement.

An Independent-Samples Kruskal-Wallis Test ($H(4) = 28.12, p < .001$) confirmed statistically significant differences in perceptions among the participant groups. A post hoc analysis, which included pairwise comparisons and applied the Bonferroni correction, is shown in Figure 6. In general, the findings suggest that seasoned pilots typically do not consider flight hours as a determinant of overall competence, whereas those in the early stages of their careers tend to place greater emphasis on the quantity of their flight hours. Gender-based analysis within participant groups highlighted differences among student pilots. The Mann-Whitney U test ($U = 62.00, Z = -2.378, p = .023$) revealed female student pilots ($N=14$, Mean Rank = 20.07) were more likely to see flight time as a reasonable measure of competence than males ($N=17$, Mean Rank = 12.65). No significant gender differences were found in other groups ($p\text{-values} \geq 0.153$). Overall, gender has little impact on pilots' perception of flight time as a measure of competence. However, among student pilots, gender influences these perceptions more distinctly.

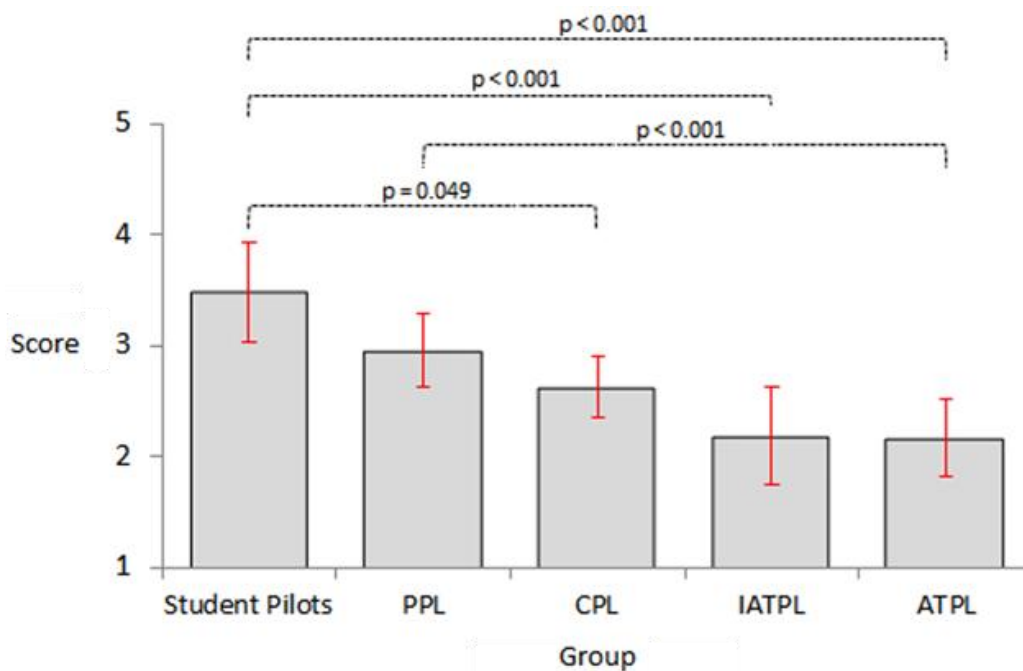


Figure 6. Survey responses: perceptions on flight time's role in pilot competence assessment
(Error bars represent 95% confidence interval)

3.4.2.2 High-Quality vs. Hour-Count Emphasis in Flight Training: Impact on Skill Acquisition

The survey revealed a broad agreement on the importance of high-quality flight training over mere flight hours, with a mean score of 4.19 and a standard deviation of 0.76. CPL holders strongly concurred (mean: 4.40, SD: 0.09), showing the highest uniformity in opinions. ATPL holders showed a slightly lower

consensus (mean: 4.06, SD: 0.14). IATPL holders (mean: 4.19, SD: 0.15), PPL holders (mean: 4.13, SD: 0.09), and student pilots (mean: 4.13, SD: 0.14) also aligned with this consensus.

The Independent-Samples Kruskal-Wallis H test revealed no significant differences in perceptions among the participant groups ($H(4) = 7.02$, $p = .135$). Additionally, the Independent-Samples Kruskal-Wallis Test on 206 participants revealed no significant gender-based differences in the perception of high-quality flight training's effectiveness, with $H(2) = .70$, $p = .705$.

3.4.2.3 Assessing Current Flight Training Standards: Uncovering Limitations

The survey results showed a general consensus on the limitations of current flight training standards, including both dual instruction and solo flying, and their impact on training outcomes. The average score of 3.81 suggests a tendency towards agreement, with a standard deviation of 0.70 indicating moderate opinion diversity. IATPL holders agreed the most (mean: 4.00, SD: 0.10), followed by CPL holders (mean: 3.92, SD: 0.09), and ATPL holders (mean: 3.87, SD: 0.12). PPL holders (mean: 3.62, SD: 0.10) and student pilots (mean: 3.74, SD: 0.11) showed milder agreement.

The Independent-Samples Kruskal-Wallis Test showed no significant differences in perceptions of flight training standards among different participant groups ($H(4)=8.93$, $p=0.063$). Furthermore, the Independent-Samples Kruskal-Wallis Test ($H(2)=0.22$, $p=0.896$) on 206 participants revealed no significant gender-based differences in the perception of flight training limitations.

3.4.2.4 Current Flight Training Standards: Assessing Technical and Non-Technical Adequacy

The survey results on current flight training standards revealed diverse opinions among participants. The overall average score of 2.86 suggests a mild disagreement with the standards' ability to meet training needs and ensure proficiency. The moderate standard deviation of 1.03 indicates significant opinion variation. Group-specific analysis revealed ATPL (mean: 2.62, SD: 0.17) and IATPL (mean: 2.38, SD: 0.19) holders generally disagreed, with IATPL holders showing stronger disagreement and uniform opinions within each group. CPL holders were neutral (mean: 3.00, SD: 0.15), whereas PPL holders leaned slightly towards agreement (mean: 3.18, SD: 0.12), with both groups showing low response variability. Student pilots (mean: 2.74, SD: 0.17) mildly disagreed, in line with the overall trend and with notable uniformity in their responses.

The Independent-Samples Kruskal-Wallis Test ($H(4) = 14.31$, $p = .006$) highlighted notable differences among participant groups. Pairwise comparisons are shown in Figure 7. Gender-based analysis within participant groups, employing the Independent-Samples Mann-Whitney U Test or Kruskal-Wallis Test,

uniformly revealed no significant differences among male, female, and non-binary pilots regarding training adequacy, with p-values ≥ 0.097 .

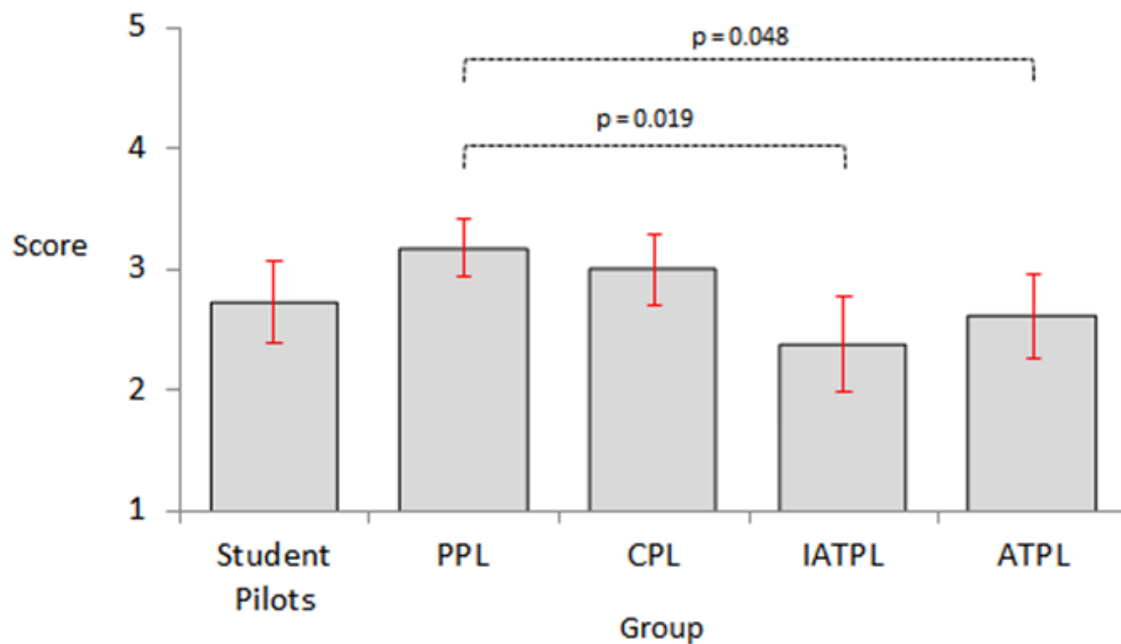


Figure 7. Survey responses: perceptions on flight training standards' efficacy and proficiency
(Error bars represent 95% confidence interval)

3.4.2.5 Objectivity in Flight Test Assessments: Evaluating the Presence of Subjectivity in Evaluation Processes

The survey results on the perception of objectivity in flight test assessments showed varied viewpoints across participant groups. The overall average score of 3.10 suggests collective neutrality. Additionally, a moderate standard deviation of 1.01 indicates a variety of perspectives among the participants. ATPL holders (mean: 3.00, SD: 0.16) exhibited neutrality with minimal variation, while IATPL holders (mean: 3.10, SD: 0.24) also showed neutrality but with slightly more variability. CPL pilots (mean: 2.80, SD: 0.14) tended towards a minor disagreement, hinting at perceived subjectivity. PPL pilots (mean: 3.04, SD: 0.13) were neutral with low variability. Remarkably, student pilots (mean: 3.93, SD: 0.09) were more inclined to agree, perceiving higher objectivity with the greatest consistency in their responses.

The Independent-Samples Kruskal-Wallis H test revealed significant differences in perceptions of flight test assessments' objectivity among the participant groups ($H(4) = 27.74$, $p < 0.001$). Bonferroni-adjusted pairwise comparisons are illustrated in Figure 8. Gender-based analysis within the PPL group revealed a notable difference: male PPL pilots ($N=39$, Mean Rank=31.23) perceived flight-test evaluations as more objective than their female counterparts ($N=16$, Mean Rank=20.13), as indicated by the Mann-Whitney U

test ($U = 438$, $Z = 2.46$, $p = 0.014$). However, no significant gender disparities were observed in the other pilot groups (p -values ≥ 0.062).

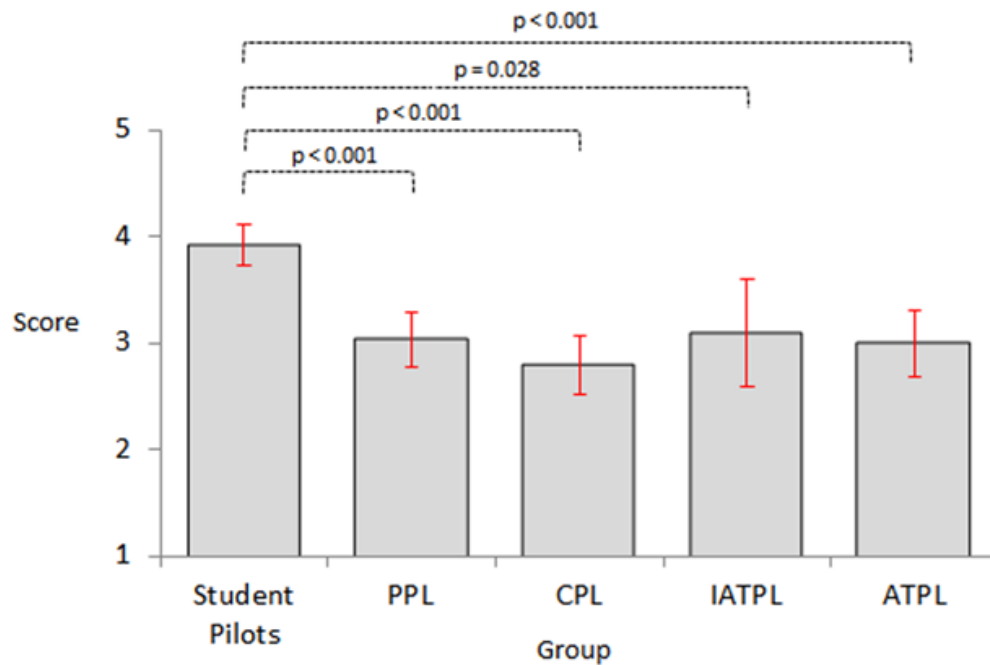


Figure 8. Survey responses: perceptions on objectivity in flight test assessments
(Error bars represent 95% confidence interval)

3.4.3 Qualitative Findings

The qualitative findings provide a comprehensive overview of participant insights gathered from open-ended survey questions regarding current pilot training standards and practices. These questions explored existing limitations and identified potential areas for improvement, focusing on both technical and non-technical flying competencies. Moreover, the survey probed limitations and opportunities for improvement in flight test assessments, eliciting recommendations for future enhancements.

The open-ended survey responses were analyzed using thematic analysis, following the methodology outlined by Braun et al. (2017). Initially, two researchers ensured the data's reliability by verifying its consistency and accuracy, crucial for maintaining the integrity of the research findings. Deductive coding was applied to see if the data aligned with established research categories, including main topics, key aspects of the research questions, or categories derived from literature or theoretical frameworks. Inductive coding was then used to create new categories from observed data patterns. This categorization process helped identify broader themes, which were rigorously validated for consistency and relevance. Subsequently, these themes were clearly defined, and their associated data were thoroughly analyzed, yielding detailed insights that enhanced our understanding of the participants' perspectives.

It is important to clarify that the findings presented in this section are derived solely from insights gathered through open-ended survey questions answered by Canadian student pilots and licensed pilots who are currently or have previously been involved in flight training. These insights reflect their direct experiences and recognize best practices within the industry, rather than conjectures made by the authors. This approach ensures that our summary is firmly anchored in the real-world perspectives and expertise of those well-acquainted with the field.

3.4.3.1 Pilot Training: Analyzing Limitations and Exploring Improvement Opportunities

Qualitative insights from the survey on pilot training were organized into three distinct themes: Training and Assessment Methods, Instructor and Resource Challenges, and Regulatory and Curriculum Development. These themes aim to enhance the effectiveness, accessibility, and relevance of pilot training, ensuring that pilots are well-equipped with the necessary skills for modern aviation.

The Training and Assessment Methods theme focuses on enhancing the quality and effectiveness of pilot training by moving beyond traditional quantitative measures like flight hours. It promotes the use of advanced simulations for complex scenarios, structured assessments, and dynamic training strategies that enhance critical thinking and decision-making skills. Meanwhile, the Instructor and Resource Challenges theme emphasizes the sustainability and quality of instruction, advocating for the professionalization of flight instructing, expansion of instructional resources, and equitable access to training facilities to improve outcomes and reduce barriers. The Regulatory and Curriculum Development theme advocates for the modernization of regulatory frameworks and curricula to reflect current aviation technologies and practices. It encourages the integration of contemporary navigational tools and team-based training formats, tailored to meet the diverse objectives of pilots pursuing different career paths in aviation. Together, these themes address specific limitations and offer improvement opportunities, as summarized in Table 3, with subsequent sections providing a detailed description of these themes.

Table 5: Pilot training: current limitations and suggested improvements

Theme	Pilot Training Limitations	Suggested Opportunities for Improvement
Training and Assessment Methods	Flight training prioritizes flight hour quantity over quality, often neglecting the qualitative aspects of pilot experience, resulting in inadequate assessments of pilot competence.	Implement a competency-based assessment system with detailed performance metrics, including documentation of training records at all training stages.
	FSTDs are underutilized for complex, emergency and non-normal scenario training, with an overemphasis on basic maneuvers.	Enhance FSTD use for nuanced scenarios while maintaining a balance with actual flight experiences.

	Solo flight training lacks a formal performance assessment, relying on subjective self-reports that may miss incorrect techniques.	Implement technology for objective data collection and formalize debrief process.
	Current flight training focuses on rote learning (procedural), overlooking the cultivation of essential decision-making skills for varied contexts.	Adopt an interactive training approach; incorporate digital resources and scenario-based exercises to bolster pilots' decision-making skills and versatility.
	High costs deter small flight schools from integrating FSTDs, favoring actual flight hours despite FSTDs' benefits.	Subsidies or financial aid for FSTDs could make them accessible to all schools.
	Current training lacks formal evaluation of student pilot's performance progression, leading to unclear skill assessments and potential training inefficiencies.	Implement a standardized system to record and accurately assess pilot proficiency development over time.
	Due to flight training guidelines treating FSTD sessions as optional, there's a tendency to underutilize FSTDs, favoring actual flight hours instead.	Make FSTD training mandatory to provide a more rounded education, covering both standard and complex flight scenarios.
Instructor and Resource Challenges	Flight instructing is seen as a temporary step (transitional phase), not a viable long-term career path, resulting in high turnover and inexperienced instructors.	Elevate instructing as a career with better pay, incentives, and clear career pathways.
	Resource shortages at flight schools result in overbooked schedules, extended training times, and a bias against local Canadian pilots in favor of foreign students and specific program enrollees.	Expand school capacities and resources, ensuring equitable access. Explore accelerated programs.
	High training costs and strict mandates at flight schools hinder skill development for student pilots needing additional training time.	Implementing financial support, scholarships, and streamlined training requirements could render pilot training more accessible and adaptable.
	Weather disruptions extend training timelines and financially impact instructors.	Implement advanced forecasting, flexible scheduling, and revised compensation. Utilize indoor training methods temporarily to stay current with flying practices during weather-related training delays.
Regulatory and Curriculum Development	Outdated regulatory standards prolong PPL and CPL training, increasing costs and delaying proficiency milestones.	Update regulations to reflect modern aviation practices.
	Flight training focuses on outdated navigation techniques, neglecting modern systems like FMS and GPS.	Update curriculum and leverage with aviation technology manufacturers to enhance training programs with current technology.
	Commercial pilot training lacks compulsory multi-crew training, inadequately preparing pilots for airline operations.	Integrate multi-crew training into the CPL curriculum to align with airline industry standards and improve pilot readiness.

	Training and standards do not distinguish between private and commercial pilot goals, leading to training inefficiencies.	Incorporate options to customize training programs to align with specific goals of student pilots, making them efficient, relevant, and safer.
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Theme: Training and Assessment Methods

The "Training and Assessment Methods" theme criticizes the reliance on flight hours to gauge pilot competency, pointing out its failure to account for the diverse learning outcomes from varied flying conditions. This method does not fully capture the range of pilot skills, leading to inconsistencies. The theme calls for a shift towards competency-based assessments, advocating for regulatory updates and collaborations with aviation bodies to establish comprehensive evaluation standards, including performance metrics at specific training stages. It suggests implementing a system for tracking competency at set training intervals and effectively managing detailed training records to provide a more accurate assessment of a pilot's abilities. Additionally, it recommends developing secure methods for documenting and sharing training records to support hiring decisions based on genuine skills instead of just flight hours.

Underscoring the underutilization of FSTDs for emergency and advanced scenario training, this theme advocates for their increased use alongside real aircraft to develop core flying skills. It also points out the lack of a standardized system for assessing solo flight training performance, noting that current post-flight debriefs rely heavily on subjective student self-reporting. This subjectivity, especially during solo cross-country flights, hinders accurate progress assessment. The theme recommends adopting objective evaluation methods for solo flights, such as using technological tools or flight data recorders to gather precise data, enabling instructors to offer targeted feedback. Additionally, it proposes a formalized debrief process, like a standardized questionnaire or checklist, to improve discussion of flying experiences and challenges, thereby enhancing training effectiveness and skill development.

Addressing the shortcomings of current flight training's procedural focus, this theme highlights its insufficiency in cultivating critical decision-making skills and thorough aviation knowledge. It advocates for the integration of digital flight preparation tools, such as simulation software, interactive platforms, and digital resources, to effectively connect theoretical learning with practical application. Furthermore, it underscores the importance of varied training environments to enrich learning outcomes. Concentrating on Pilot Decision Making (PDM) and applying scenario-based training that merges in-flight and FSTD experiences, the proposed strategy seeks to enhance pilots' adaptability and decision making across diverse situations.

Identifying the high costs of quality FSTDs as a significant obstacle in flight training, this theme advocates for subsidies or financial aid from regulatory bodies to enhance FSTD accessibility. It argues for

an integrated training model that combines actual flying and simulations for a cost-effective approach. Additionally, it highlights the lack of a formal system to track a pilot's skill development during training. Current logbooks, which record flight hours and exercises, fail to measure proficiency accurately, leading to potential inefficiencies in training. The absence of standardized evaluation for maneuvers complicates skill assessment, often resulting in prolonged, expensive training. The theme suggests adopting a standardized evaluation system with clear proficiency benchmarks to identify areas for improvement and objectively determine flight test readiness, improving training transparency and effectiveness in developing skilled pilots.

Finally, the theme stresses the necessity of making FSTD training mandatory to address instructors' bias towards real flight hours for logbook and billing purposes, which often sidelines FSTDs' critical role in complex scenario training. Implementing compulsory FSTD sessions will guarantee a more rounded training experience, boosting safety and proficiency. It also highlights the importance of educating both students and instructors on FSTD benefits, aiming to shift the training focus towards a balanced approach that prepares pilots for diverse flying conditions.

Theme: Instructor and Resource Challenges

The "Instructor and Resource Challenges" theme underscores the issue of high turnover rates among flight instructors, often viewed as a stepping stone to airline jobs rather than a long-term profession. This leads to a reliance on less experienced pilots for foundational training, a problem compounded by low pay and variable demand for pilots. Additionally, this cycle frequently results in a scarcity of seasoned instructors available for training new flight instructor candidates or those seeking advanced instructor certifications. To address this, the theme proposes enhancing the instructor role through improved compensation, incentives for long-term commitment, and career advancement opportunities within flight schools. These measures aim to position instructing as a viable long-term career option, helping to retain experienced instructors and ensure high-quality training.

Resource constraints within flight schools, including limited aircraft availability and infrastructure, contribute to overbooked schedules and prolonged training periods where license delays can span years due to limited flying opportunities. This situation is worsened by some schools' preference for foreign students or those enrolled in specific academic programs, disadvantaging local pilots. The theme advocates for flight school resources expansion, equitable scheduling systems, and accelerated programs to expedite the licensing pathway. Funding from regulatory bodies or government grants could support the necessary expansions, ensuring access to quality training. Fair access for all students and faster training options aim to reduce the time to obtain licenses, facilitating quicker transitions to airline careers and minimizing potential income losses for student pilots.

Financial challenges in flight training, especially for those requiring additional practice, result in higher costs and can limit training frequency, negatively impacting skill development. Strict training protocols at some flight schools further contribute to students achieving only minimal passing criteria, hindering skill acquisition. To overcome these financial hurdles, the theme underscores the introduction of supportive measures such as airline and government subsidies, increased financial aid, scholarships, and specialized loan programs for aspiring pilots. Additionally, re-evaluating and possibly simplifying training requirements may reduce financial pressure, allowing for more tailored training that suits individual learning speeds without sacrificing educational quality.

Lastly, the theme points out that weather-related challenges often delay flight training, as students face frequent cancellations, affecting both their progress and instructors' financial stability due to lack of compensation for canceled sessions. Recommendations include using advanced weather forecasting, implementing flexible scheduling, improving instructor compensation for cancellations, and investing in indoor training facilities with FSTDs. These measures aim to ensure consistent training progress despite adverse weather conditions.

Theme: Regulatory and Curriculum Development

The "Regulatory and Curriculum Development" theme emphasizes the need to update flight training regulations and curricula to reflect modern aviation practices. Current minimum training requirements PPL and CPL are outdated, often leading student pilots to exceed the regulatory minimums, such as requiring 60-80 hours for PPL proficiency against the mandated 45 hours. This discrepancy prolongs training and increases costs for student pilots. The theme calls for a thorough revision of these standards to include contemporary aviation technologies and methods, aiming to make training more efficient and cost-effective.

Addressing the gap in navigation training, this theme critiques outdated navigation training (VOR and NDB) for not preparing pilots for modern technologies like FMS and GPS. While foundational knowledge of traditional navigation aids remains valuable, especially in technology failure scenarios like GPS outages, it should not be the sole focus. The theme recommends updating curricula to cover these advanced systems also, using FSTDs that reflect today's aircraft cockpits. To keep training current, it suggests forming partnerships with technology manufacturers for the latest in FSTD technology.

On the topic of multi-crew training, this theme pinpoints a significant shortfall in Canada's commercial pilot training, which omits essential preparation for collaborative operations in commercial airlines. It suggests adding multi-crew training to the CPL curriculum to provide realistic training experiences, covering crew resource management (CRM) and standard procedures, and allowing student pilots to practice roles of both pilot and first officer. Establishing partnerships between flight schools and airlines

could customize training for multi-crew operations and specific airline procedures, ensuring training relevance and smoothing the path to airline careers.

Finally, this theme reflects on the evolving needs of pilot training, noting the diminished relevance of traditional exercises like diversion and precautionary landings in commercial aviation dominated by IFR and well-equipped runways. It advocates for a training model more attuned to the operational realities and roles pilots will face, emphasizing GPS over outdated paper maps for planning. Tailoring training to equip pilots with relevant skills promises enhanced proficiency and safety in the cockpit, preparing them for the demands of contemporary aviation.

3.4.3.2 Flight Test Assessment: Analyzing Limitations and Exploring Improvement Opportunities

Qualitative insights on flight test assessment were organized into five distinct themes: Standardization and Fairness in Flight Testing, Relevance and Modernization of Training and Assessment, Addressing Biases and Ensuring Objectivity in Assessments, Comprehensive and Adaptive Pilot Training, and Regional Variability and National Skill Harmonization. These themes aim to enhance the fairness, relevance, effectiveness, and adaptability of flight test assessments, ensuring that pilots are thoroughly evaluated with the skills necessary for modern aviation.

The Standardization and Fairness in Flight Testing theme focuses on eliminating the variability in testing procedures and examiner approaches that can affect the difficulty and fairness of flight tests. The Relevance and Modernization of Training and Assessment theme emphasizes updating training and assessment methods to align with contemporary aviation practices. The Addressing Biases and Ensuring Objectivity in Assessments theme seeks to mitigate biases introduced by examiners' prior knowledge of student pilots, economic incentives, and regional disparities. The Comprehensive and Adaptive Pilot Training theme addresses the need for training that prepares pilots for real-world challenges beyond standardized tests. The Regional Variability and National Skill Harmonization theme tackles the challenges posed by regional differences in Canada that affect flight test outcomes and pilot skill development. Together, these themes address specific limitations and offer improvement opportunities, as summarized in Table 4, with subsequent sections providing a detailed description of these themes.

Table 6: Flight test assessment: current limitations and suggested improvements

Theme	Flight Test Assessment Limitations	Suggested Opportunities for Improvement
Standardization and Fairness in Flight Testing	Non-standardized pre-flight assessments lead to inconsistent pre-flight briefings amongst examiners.	Adopt a standardized pre-flight assessment framework with set durations and uniform topics.
	Ambiguous definitions of deviations in flight test guide allow for subjective interpretations	Introduce precise, objective criteria for deviations. Conduct periodic examiner

	by examiners, leading to inconsistent evaluations.	training to standardize these evaluation criteria.
	Variability in examiner approaches and external conditions affects test difficulty.	Establish standardized guidelines for each exercise, with a focus on consistent scenario and environment selection.
	Grading system for each exercise focuses on the lowest-performing criterion, overshadowing a pilot's overall proficiency and strengths.	Adopt a balanced grading approach that evaluates each criterion individually within an exercise.
Relevance and Modernization of Training and Assessment	Night and seaplane ratings lack formal testing, potentially overlooking critical flying challenges.	Introduce standardized, comprehensive testing for both ratings, including scenario-based assessment.
	Flight tests rely on outdated navigation aids, misaligning with current GPS-focused practices.	Update test procedures to emphasize GPS and modern navigation methods.
	Certain aspects of pilot written exams focus on outdated theories, missing practical skills relevant to modern aviation.	Revamp exams to cover practical knowledge, including decision making and modern navigational tools.
Addressing Biases and Ensuring Objectivity in Assessments	Bias from economic incentives and performance metrics leads to uneven testing rigor and compromises assessment integrity.	Implement a transparent system with random examiner assignments along with periodic ethical training.
	Examiners' knowledge of students' past performances tends to introduce bias, affecting the fairness of flight test evaluations.	Rotate examiners and enforce objectivity and bias awareness with periodic training.
	In-house examiners and their geographic limits lead to institutional bias, affecting the impartiality of evaluations.	Diversify the examiner pool by appointing independent, external examiners. Revise examiner performance metrics; focus on broader criteria beyond pass-fail rates.
Comprehensive and Adaptive Pilot Training	"Teaching to the test" limits real-world preparedness, leading to inadequate skill development.	Shift to versatile, scenario-based training, with varied emergencies. Periodic ethical training to emphasize training practices focused on skill development as opposed to just test passing.
	Instructors' resistance to new methods and technology can make their training less relevant to modern aviation.	Update instructors' recurrent training to include new techniques, safety protocols, and modern technology. Introduce periodic instructor evaluations.
Regional Variability and National Skill Harmonization	Regional differences in Canada affect flight test outcomes and skill development due to varied geographical conditions.	Expand curriculum to include all relevant geographical conditions and scenarios.

Theme: Standardization and Fairness in Flight Testing

The theme "Standardization and Fairness in Flight Testing" highlights the lack of fairness and uniformity in flight test evaluations due to non-standardized pre-flight assessments and subjective performance deviation (critical, major, and minor) interpretations by examiners. It proposes creating a standardized framework for pre-flight assessments to unify briefing content and lengths and recommends defining clear, objective criteria for evaluating deviations. Additionally, it suggests regular examiner training to promote consistency and fairness in evaluations. The theme also points out the inconsistency in flight test difficulty arising from examiners' subjective assessments, notably in scenarios such as simulated engine failures where the scenario choice affects the test's difficulty level. Variability is further increased by factors like weather and air traffic conditions on the day of the test, impacting fairness and performance. To address these issues, it suggests establishing standardized guidelines for exercises to ensure consistent scenario and condition selection. It also recommends uniform training and evaluation programs for examiners to guarantee fair assessments. Moreover, the current grading system for flight test exercises focuses on the lowest-performing criterion, which can potentially undermine a pilot's overall proficiency. In simpler terms, if a pilot performs well in several areas but struggles in one, the grading system emphasizes the lowest score. This approach might give the impression that the pilot lacks overall proficiency, even though they may excel in other aspects. Such a method can obscure the pilot's strengths and lead to an imbalanced assessment of their true abilities. This grading practice also does not align with ICAO recommendations, which advocate for a more holistic evaluation. A more effective strategy can be to assess each performance criterion individually within an exercise. This improved approach would offer a more comprehensive and balanced evaluation, effectively highlighting both strengths and weaknesses. Consequently, this can enhance the overall quality of training and assessment by ensuring that while a pilot's deficiencies are addressed and improved upon, their competencies in other areas are also recognized and appropriately valued.

Theme: Relevance and Modernization of Training and Assessment

The "Relevance and Modernization of Training and Assessment" theme highlights deficiencies in current flight test assessments, particularly for night and seaplane aviation ratings, where pilots receive ratings without formal tests, missing out on challenges like navigating in low light or executing short takeoffs from water. It suggests implementing comprehensive, standardized tests and scenario-based training for these ratings to prepare pilots for various situations. The theme also critiques the use of outdated navigation aids like NDBs and ADFs in assessments, despite the advent of GPS technology, recommending a shift towards GPS and modern navigation training to align with contemporary aviation standards. Additionally, the theme critiques outdated components of pilot certification written exams, emphasizing theoretical knowledge less

relevant due to GPS and EFBs like ForeFlight. It recommends updating exams to focus on practical skills, including PDM, CRM, and Human Factors, through scenarios that employ modern tools. This update aims to blend theoretical understanding with essential practical skills for today's aviation, enhancing pilot proficiency and safety in real-world scenarios.

Theme: Addressing Biases and Ensuring Objectivity in Assessments

The theme "Addressing Biases and Ensuring Objectivity in Assessments" identifies bias in flight test evaluations stemming from economic motivations or examiners' interests in maintaining high pass rates, leading to inconsistencies and potentially lenient assessments. It suggests establishing a transparent, standardized system for evaluating and compensating examiners, enhanced by regular audits, performance reviews, and random examiner assignment to students, to uphold fairness and integrity in assessments. The theme also suggests rotating examiners and providing bias awareness training to mitigate bias, especially when an examiner is familiar with a student's history, ensuring evaluations focus on objective criteria for fairness. Furthermore, it addresses institutional bias stemming from in-house examiners and the geographical limitations faced by non-in-house examiners, proposing the adoption of independent, external examiners and the expansion of examiners' operational areas to prevent flight schools from favoring certain training methods. This approach necessitates policy changes by aviation authorities and the updating of performance metrics to assess examiners on criteria beyond mere pass-fail rates, with the goal of enhancing pilot skill evaluation and the fairness of testing.

Theme: Comprehensive and Adaptive Pilot Training

The theme "Comprehensive and Adaptive Pilot Training" addresses the issue of training primarily aimed at passing flight tests, which may overlook preparation for real-world scenarios. It advocates for a broader training approach that equips pilots with skills for diverse situations, emphasizing emergency simulations and scenario-based training for critical decision-making skills. This method aims to prepare student pilots for exams and flying's unpredictability. It also emphasizes the need for uniform assessment criteria to avoid training tailored to specific examiners and advocates for ethical training practices that emphasize skill development beyond merely passing tests. In addition, the theme points out the reluctance of seasoned flight instructors to adopt new methodologies and technologies, preferring traditional practices over modern techniques and safety protocols. This resistance can render their training outdated for today's aviation standards, potentially overlooking important contemporary skills like situational awareness in favor of classic aircraft control. To address this, it proposes regular updates to instructor training programs, incorporating the latest techniques, safety protocols, and technological advancements to ensure their instruction meets current industry demands.

Theme: Regional Variability and National Skill Harmonization

The "Regional Variability and National Skill Harmonization" theme underscores disparities in flight test skill levels across Canada, attributed to varying geographical and environmental conditions. For instance, emergency landing maneuvers vary significantly with terrain, making such maneuvers in flat regions like the Prairies less challenging than in the mountainous areas of British Columbia, thus leading to regional skill differences. It suggests expanding the training curriculum to cover diverse conditions across Canada's varied airspace, emphasizing the development of adaptable decision-making skills to standardize pilot proficiency nationwide. This approach ensures pilots acquire skills for all flying conditions, aiming to unify training standards across the country and achieve consistent competence among student pilots, regardless of their training location.

3.5 Discussion & Conclusion

3.5.1 Do student and licensed pilots regard accumulated flying hours as a reliable indicator of pilot competence?

Historically, flight hours have served as a key benchmark for evaluating pilot proficiency. However, as the civil aviation sector advances with technological innovations and evolving safety paradigms, the reliability of flight hours as the sole measure of pilot competence is increasingly questioned. This study investigates whether student and licensed pilots view accumulated flying hours as a dependable indicator of pilot skill, examining perceptions across the civil aviation community.

Overall, pilots consider flight hours to be an inadequate metric for quantifying pilot competence, particularly among those with extensive flying experience. Experienced pilots express more skepticism, highlighting that true proficiency extends beyond mere airtime. Conversely, novice pilots tend to regard flight hours as a valuable skill indicator, suggesting that perceptions of competence evolve significantly with accumulated training experience. During the early stages of pilot training (e.g., 0-50 hours), flight training adheres to well-established guidelines and manuals, featuring a clear structure and standardized steps. As a result, student pilots' skill progression is generally consistent as training hours accumulate. However, for experienced pilots (e.g., over 500 hours), the development of their skills is influenced by various situational factors, such as their job type (e.g., flight instructor or bush pilot), exposure to complex flight conditions (e.g., adverse weather, busy airspace), and the level of mentorship received from senior pilots (e.g., flying solo versus with a captain). Consequently, experienced pilots argue that the rich complexity and diversity of their experiences cannot be accurately captured by flight hours alone. The disparities in perspectives on the importance of flight hours among study participant groups, spanning different experience levels and, to some extent, gender differences among student pilots, highlight the

urgent need to critically re-evaluate the traditional hour-based metric for assessing pilot competence. The study advocates for a shift towards a competency-based evaluation framework, moving from a purely quantitative assessment to one that values the quality and diversity of flight experiences. This requires a collaborative effort from aviation regulators, training bodies, and industry stakeholders to redefine pilot competence. By focusing on systematic tracking of pilots' skill development and maintaining detailed performance records throughout the training process, this competency-based framework can offer a comprehensive insight into a pilot's skill set, which could lead to more informed hiring decisions based on a comprehensive skill profile rather than solely on flight hours. It also highlights the necessity for secure, privacy-aware methods for recording and sharing training data, ensuring evaluations meet modern data protection standards. Furthermore, recognizing gender differences in flight hour perceptions emphasizes the need for inclusive assessment criteria and training methods, enhancing pilot evaluation accuracy, safety, and efficiency while adhering to data security and privacy principles.

By promoting a nuanced and comprehensive assessment approach, this study contributes to the ongoing dialogue on improving pilot competence evaluation for general aviation. It calls for collaboration across the aviation industry to achieve excellence in general aviation pilot training ensuring evaluations remain robust, relevant, and aligned with the highest safety and professionalism standards in this rapidly evolving field.

3.5.2 Do student and licensed pilots perceive current pilot training practices and standards as adequately addressing pilots' educational and practical needs, ensuring key instructional and assessment elements are met?

In the rapidly evolving landscape of civil aviation, the adequacy of pilot training practices and standards in meeting the educational and practical needs of pilots emerges as a critical inquiry. This study, motivated by the question of whether current general aviation pilot training practices and standards adequately address all key instructional and assessment elements, aims to explore the perceptions of both student and licensed pilots on this matter.

The study reveals that, although current pilot training practices and standards are fundamentally strong, they do not fully meet the modern demands of pilot training as recognized by study participants from various experience levels and gender identities. There is a unanimous recognition of the need for improvement, with both quantitative and qualitative findings pinpointing specific areas for development in technical, non-technical, and decision-making competencies within pilot training. Key recommendations include integrating FSTD training for emergency and non-normal scenarios to complement real aircraft experience, adopting objective and standardized assessment methods, especially for solo flight training, and implementing systems to track pilot proficiency development. Modernizing the curriculum to incorporate

advanced aviation technologies, critical decision-making skills, and modern navigation tools, including GPS and flight management systems, is emphasized. Additionally, accommodating regional variability to allow for national skill harmonization has been deemed essential. Addressing flight instructor turnover and resource constraints with better compensation, incentives, and career pathways, alongside regulatory support for high-quality FSTD access, is also critical.

The study underscores the diverse perceptions of flight test assessment objectivity among student and licensed pilots surveyed for the study. Student pilots, viewing these evaluations through the lens of their novice status, tend to perceive them as more objective, equating them with fairness and a well-structured learning process. In contrast, licensed pilots, armed with greater experience, approach these assessments with a critical eye, often adopting neutral or slightly skeptical attitudes. This variance underlines how different stages of pilot training influence perceptions of fairness and objectivity in assessments. Furthermore, the research identifies a significant gender disparity among PPL holders, where male pilots are more inclined to view flight test evaluations as objective compared to their female counterparts. This finding signals the importance of developing targeted strategies to ensure that assessments are perceived as equally fair and objective, irrespective of the pilot's gender. Surveyed student and licensed pilots advocate for enhanced standardization and fairness in flight testing, suggesting a framework that incorporates precise, objective criteria for performance evaluation. Such a framework could feature a balanced grading system and regular training for examiners to mitigate biases and guarantee consistency in evaluations. To bolster testing rigor and integrity, the introduction of a transparent system with randomly assigned examiners is recommended. Additionally, addressing institutional bias through the diversification of the examiner pool, including the integration of independent, external examiners, is proposed as a means to further ensure the equity and objectivity of flight test assessments.

These reforms collectively strive to elevate the quality and effectiveness of pilot training, equipping pilots to navigate the complexities of modern aviation. They advocate for a collaborative dialogue among the pertinent stakeholders to harmonize training standards with the educational and practical needs of pilots, aiming towards a future with enhanced flight training standards.

3.5.3 Comparison of insights from current study with existing regulatory standards and guidelines

Insights from survey participants (student and licensed pilots), gathered through open-ended survey questions, have revealed several limitations and potential improvements in current Canadian pilot training, flight test assessments, and evaluation practices. Given the strong global reputation of EASA as an aviation authority, its strict adherence to ICAO standards, and its efforts to ensure consistent safety measures across member states [185–188], EASA practices were chosen for comparison with the improvement opportunities

suggested by survey participants. This comparison aims to explore opportunities that have not yet been adopted by EASA, and identify best practices from a global perspective. The comparison is organized into two categories for clarity: pilot training and flight test assessment. Overall, while EASA's established practices align well with many recommendations from survey participants, there are distinct areas where Canadian insights could further enhance EASA's practices. These suggestions add new dimensions to the training and assessment processes, offering valuable insights for global aviation training enhancements.

Pilot Training

EASA has implemented CBTA primarily in commercial air transport under its Part-FCL (Flight Crew Licensing) guidelines and regulations [120]. However, its application in other civil aviation sectors, like general aviation and non-commercial operations, remains limited. EASA encourages the adoption of these training methodologies across various sectors, though mandatory regulations focus predominantly on commercial air transport. This makes CBTA more prevalent in advanced training stages rather than at the ab initio (beginning) level. Survey participants, on the other hand, advocate for the integration of competency-based training from the onset of pilot training to cultivate a competency-focused learning trajectory across all areas of civil aviation, including general aviation and non-commercial sectors. They also recommend employing objective evaluation methods for solo flights, such as technological tools or flight data recorders, to refine training methods and enhance pilot competency assessments. While EASA recognizes the importance of FSTDs in training for both standard and complex scenarios [189–191], suggestions from survey participants include mandating FSTD training to ensure comprehensive coverage of all training scenarios. They also highlighted the financial hurdles flight schools encounter, proposing financial aid strategies to facilitate the integration of FSTDs into training programs, an area not explicitly addressed by EASA. Furthermore, although EASA advocates formal evaluations to track student pilot progress [119], survey participants propose developing a system to monitor pilot competency at set intervals, manage detailed training records, and establish secure methods for documentation and sharing, aiming to support hiring decisions based on actual skills rather than merely flight hours.

In Canada, flight instructing is often seen as a temporary career step, resulting in high turnover and less experienced instructors. Although EASA offers a variety of training and certification programs to help instructors advance their careers, including initial and recurrent training, standardization programs and specialized courses to improve instructional techniques [119,192,193], survey participants have proposed specific strategies to elevate flight instructing as a long-term career option with better compensation and incentives. They also addressed the challenges of overbooked schedules and prolonged training periods due to resource shortages at flight schools or weather disruptions. While EASA ensures flight schools have the necessary infrastructure and aircraft for quality training [194], insights from survey participants go further,

recommending advanced forecasting, flexible scheduling, and revised instructor compensation strategies to manage these issues effectively. This includes using indoor training methods temporarily during weather disruptions. Additionally, to support student pilots facing high training costs and needing more time to develop skills, survey participants have proposed financial measures such as subsidies, scholarships, and specialized loan programs.

Survey participants identified outdated regulatory standards as a significant challenge that prolongs the duration of PPL and CPL flight training, increases costs, and delays proficiency milestones. In contrast, EASA has proactively updated its regulations and aligned its training programs with contemporary aviation practices and technological advancements, thereby reducing unnecessary training costs and delays [119,120,190,193,194]. EASA's curriculum now includes modern navigation training with systems like FMS and GPS, ensuring that pilots are proficient with the latest technologies. Similarly, survey participants have proposed updates to the Canadian training framework. They advocate not only for active curricular updates but also for forming partnerships with aviation technology manufacturers to keep training programs at the forefront of technological trends. Additionally, they emphasize the need to tailor training programs to the specific goals of student pilots, thereby enhancing their efficiency, relevance, and safety. A key recommendation is the integration of multi-crew training into the CPL curriculum to align more closely with airline industry standards and significantly improve pilot readiness. While EASA has integrated multi-crew training into its broader training framework through a separate airline pilot standard multi-crew coordination (APS MCC) program and advanced stages of the Airline Transport Pilot License (ATPL) training [120], this is not yet a requirement for the CPL curriculum.

Flight Test Assessment

Survey participants identified several issues with flight test assessments, including non-standardized pre-flight assessments that lead to inconsistent briefings among examiners, and ambiguous definitions of deviations in flight test guides that allow for subjective interpretations. These issues result in inconsistent evaluations and overshadow a pilot's overall proficiency and strengths. In contrast, EASA has made significant strides in standardizing pre-flight assessments, establishing objective criteria for deviations, creating standardized guidelines for conducting flight exercises, and adopting a balanced grading approach, aligning well with improvements also suggested by survey participants [119,194,195].

Additionally, survey participants have noted that night and seaplane ratings often lack formal testing, potentially missing critical flying challenges. While EASA mandates specific training requirements for these ratings, it does not include standardized comprehensive testing [194,196]. Therefore, focusing on standardized, scenario-based testing for night and seaplane ratings could enhance EASA's established practices.

Moreover, survey participants point out that certain aspects of pilot written exams are based on outdated theories and lack practical skills relevant to modern aviation. Although EASA has updated its theoretical knowledge requirements to include practical skills and modern navigation tools [197], there is a call for a comprehensive revamp of written exams to further integrate relevant practical knowledge, such as decision-making and contemporary navigational tools. These changes could align theoretical assessments with current aviation demands.

Survey participants also raised concerns about biases and a lack of objectivity in flight test assessments. Economic incentives and performance metrics for instructors can potentially lead to uneven testing rigor and compromised assessment integrity. While EASA promotes consistent examiner training and standardized evaluation criteria [195], recommendations from survey participants include implementing measures such as random examiner assignments, periodic ethical training, rotating examiners for retests or when familiar with a student's history, employing independent external examiners to mitigate institutional bias, and expanding examiners' operational areas to prevent favoritism in training methods. These improvements could further enhance the fairness and objectivity in flight test assessments.

Additionally, survey participants have identified "teaching to the test" as a significant limitation to real-world preparedness, leading to inadequate skill development. They also note resistance from instructors to adopting new methods or technologies, which makes the training less relevant and effective. In contrast, EASA has implemented EBT, which focuses on scenario-based training and directly addresses real-world preparedness by incorporating varied emergency scenarios [119]. However, the adoption of EBT outside of commercial air transport remains limited. To address these issues, survey participants advocate for the expansion of scenario-based training for ab initio (initial) pilot training, including in general aviation and non-commercial sectors, to enhance real-world preparedness. They also suggest including periodic ethical training for instructors to shift the focus from merely passing tests to actual skill development.

Finally, regional differences in Canada affect flight test outcomes and skill development due to varied geographical conditions. While, EASA's training programs, particularly through EBT, incorporate a variety of scenarios [119], survey participants suggest expanding the EBT framework to include all relevant geographical conditions and scenarios to harmonize skills nationwide. This approach would ensure consistent skill development across different training environments, highlighting the need for a more comprehensive training strategy that accommodates regional variability.

3.5.4 Comparing Past Studies and New Research Outcomes

Previous research broadly identified inadequacies in Canada's pilot training and licensing standards and practices without providing detailed recommendations or identification of specific areas needing

enhancement. They highlighted the general need for enhanced protocols that encompass both technical and non-technical skills, as well as the incorporation of advanced technologies and methodologies. Building on this foundation, the current study introduces new insights and offers a thorough examination of the limitations in pilot training and licensing standards and practices. It distinguishes itself by offering a detailed analysis of the perceptions of pilot training from both students and licensed pilots, forward-thinking recommendations for training and assessment reforms, and advocating for a more inclusive and comprehensive approach to pilot training and competency evaluation. These recommendations chart actionable pathways for enhancing training effectiveness, unexplored in previous studies, with the potential to significantly improve the development of more effective and equitable training and assessment protocols. Moreover, the study underscores the importance of collaborative dialogue among aviation regulators, training bodies, and industry stakeholders in harmonizing training standards, highlighting the necessity of a unified approach for systemic reforms. This emphasis on collaboration is vital for addressing the complexities of modern aviation. Uniquely, the study identifies gender disparities in perceptions, suggesting strategies to ensure assessments are perceived as equally fair and objective across genders. This focus on inclusivity and fairness introduces a new dimension to the discourse on pilot training and assessment, enriching the conversation with perspectives on gender equity.

Comparing the findings from previously published studies and the current findings reveals areas of novelty, highlighting the current work's significant contributions to the field of pilot training and competency assessment. The novel insights, fresh perspectives and practical recommendations offered by this study underscore its pivotal role in driving forward the understanding and implementation of more effective, equitable, and inclusive practices in general aviation pilot training and assessment.

3.5.5 Limitations & Future Research

The gender composition of the 206 participants in the study was uneven, consisting of 73.8% males, 25.2% females, and 0.8% non-binary individuals. Such imbalance restricts in-depth gender-based analysis, possibly missing nuances among different gender groups. Future research could strive for balanced gender representation.

The study broadly examined training and assessment practices across general aviation, without distinguishing between the specific license certifications or ratings that fall within this sub-sector of general aviation. While this approach allowed for an overarching understanding of the training landscape and encouraged participants to reflect on their entire training journey, it may have overlooked specific nuances and challenges unique to different license certifications or ratings within general aviation. Future research could address this limitation by conducting a survey study that categorizes inquiries based on different licensing stages or ratings. This structured approach would enable the collection of specific feedback,

offering more granular insights into the unique challenges and effectiveness of each licensing or rating level. Such a targeted study could enhance our understanding of the specific needs and experiences of pilots at various certification or rating levels, thereby facilitating a more nuanced analysis of the training and assessment practices within general aviation.

The online survey method in this study limits follow-up questioning and participant clarification, hindering deeper insight into their perspectives. Future research could be enhanced by incorporating focus group interviews, which can allow for more direct interaction and detailed exploration of participant views. Additionally, employing mixed-method approaches, such as combining quantitative surveys with focus group discussions, could be another method to facilitate a more thorough investigation of responses. These can enable clarification, elaboration, and detailed examination of complex topics.

The study included 31 student pilots (15.1%) and 175 licensed pilots (84.9%), with licenses distributed as follows: 55 PPLs (26.7%), 52 CPLs (25.2%), 21 IATPLs (10.2%), and 47 ATPL (22.8%). Although the licensed pilot group's diversity strengthens the study's conclusions, the underrepresentation of student pilots and IATPL holders suggests room for a broader perspective. Future research could aim to include a more expansive and balanced participant mix, particularly by increasing student pilots and less prevalent license types, to enhance insights into pilot training and evaluation.

There is the potential for self-selection bias, particularly among licensed pilot respondents. Individuals who chose to participate in the survey may have held stronger views about the limitations of existing licensing practices—especially those who felt underserved or believed that their competence and training needs were not adequately recognized by the current hours-based model. This may have introduced a degree of bias in the representation of pilot perspectives. Although efforts were made to diversify viewpoints, future research could further strengthen generalizability by adopting targeted sampling strategies to capture a more representative cross-section of the general aviation pilot population. Longitudinal studies that follow pilot cohorts over time—across different training pathways and varying levels of industry exposure—could provide deeper insight into how perceptions of training practices evolve not only throughout the licensing process but also with the accumulation of flight experience across different operational contexts.

The scope of this survey is confined to Canada, focusing solely on student and licensed pilots within general aviation of the Canadian civil aviation sector. This geographical limitation constrains the applicability of the findings to pilot training and assessment practices globally. Future research could broaden the scope by examining these practices in various countries, enabling a comparative analysis to uncover unique challenges and best practices with worldwide applicability.

The use of direct evaluative language in certain survey questions may have shaped how participants framed their responses, potentially encouraging a more critical lens. While the intent was to encourage thoughtful reflection, such phrasing could influence participants to focus more on challenges or areas for improvement. Future research could benefit from incorporating more balanced question framing, combining evaluative and affirming language, to allow participants to reflect on both strengths and weaknesses in their training experience.

Chapter 4 (Study 3)

Exploring Technology Acceptance of Flight Simulation Training Devices and Augmented Reality in General Aviation Pilot Training

4.1 Introduction

The 21st century has brought profound transformations across various facets of life, largely driven by the widespread adoption of technological innovations. Advancements such as smartphones, digital ecosystems, and collaborative communication platforms have reshaped the consumer-technology landscape, raising expectations for quality, innovation, accessibility, and sustainability. Emerging technologies like artificial intelligence, machine learning, the Internet of Things, and cloud computing have created new opportunities and enhanced solutions across various sectors[110,111,113–115]. However, despite such significant technological breakthroughs transforming numerous industries, the general aviation (GA) sector of civil aviation remains technologically behind. Advanced technologies such as flight simulation training devices (FSTDs)—synthetic training devices or simulators certified for pilot training—remain notably underutilized within GA sector, particularly for beginner pilots[109,128,198–203]. GA includes all private and non-commercial aviation activities, excluding scheduled airline and cargo services[52,204]. This broad sector covers private flying, non-scheduled commercial operations, and specialized services, such as flight training, agricultural aviation, law enforcement, medical air transport, aerial surveying, air tourism, corporate aviation, disaster relief services etc. It commonly serves as an essential foundation for pilots before they progress to commercial air transport (CAT) sector, which encompasses scheduled passenger and cargo services[106,205]. Existing research highlights significant value of simulation training[203,206–212]; yet the GA sector predominantly relies on traditional training methods. This reliance is particularly concerning given the heightened focus on human factors today, as national GA statistics from around the world reveal that human error is implicated in up to 85% of all GA accidents, often due to poor situational awareness[203,213–216].

FSTDs play an indispensable role in the CAT sector due to the exorbitant costs associated with using actual commercial aircraft for training purposes[203,204,217]. For example, employing a Boeing 787 solely for training is financially unsustainable. Instead, commercial aviation training begins with sophisticated FSTDs, specifically high-end full flight simulators (FFS), which allow pilots to gain initial experience in a cost-effective, simulated environment. Pilots then continue their training as first officers under the supervision of experienced captains, combining high-fidelity simulation with real-world flying experience. Because using an actual aircraft for training is economically prohibitive, airlines invest heavily in these

FSTDs, which replicate the full flying experience—including realistic motion, visuals, and sound—effectively mimicking operations of real aircraft at a fraction of the cost. Consequently, in CAT pilot training, FSTD training is not merely an option; it is a necessity. In contrast, GA pilot training presents different considerations. At this level, training with both real aircraft and FSTDs is cost-effective, allowing flexibility for training to be completed entirely in an aircraft or through a combination of actual flight and simulation-based methods.

FSTDs can offer significant benefits in general aviation training, particularly for novice pilots[95,128,198,202–204,206–208,210,211,217–219]. Among the few notable benefits are: they provide a safe, controlled environment to practice high-risk scenarios, such as engine failures, emergency landings, system malfunctions, and degraded visual conditions—situations that are unsafe or impractical to replicate in real aircraft. Beyond emergency training, FSTDs enable repetitive practice of maneuvers and procedures without time constraints, helping student pilots refine techniques, and build proficiency, particularly during the transition to solo flying. Unlike real aircraft training, which is often constrained by unpredictable weather and operational limitations, FSTDs allow tailored practice of specific skills, such as crosswind landings, by simulating conditions on demand. This capability enhances procedural understanding, sharpens decision-making, and ensures uninterrupted training during adverse weather or scheduling delays. Additionally, advanced debriefing tools, including session recordings and re-playable scenarios, provide instructors with detailed, data-driven insights to identify errors and recommend targeted improvements, accelerating skill development. These advantages come with significantly lower training costs compared to real aircraft training, while also reducing emissions and promoting sustainable aviation practices. However, it is important to acknowledge that FSTDs have limitations in replicating the physical sensations and haptic feedback required for motor-intensive flight operations, such as takeoffs, where the feel of controls, aerodynamic forces, and vibrations play a critical role. While high-fidelity simulators can mitigate these gaps to an extent, real aircraft training remains fundamental for developing motor skills, mastering physical flight dynamics, and building confidence in practical flight settings. Therefore, FSTDs should be viewed as complementary tools that enhance and reinforce flight training, offering a safe, cost-effective, and efficient solution for areas where the use of real aircraft may be impractical or inadequate and may not fully address training needs.

Historically, the acceptance of FSTDs in GA sector, particularly at the ab initio (beginner) level, has been limited[198,201–203,220,221]. Often viewed as less capable and not cost-effective, this perception has contributed to their low adoption rate. This perception has been further influenced by the regulatory framework governing the use of FSTDs in GA, which allows flying schools, instructors, and student pilots to opt for simulation training based on personal preferences and perceived benefits. Civil aviation

regulations categorize simulation training for GA as optional, with specific limits[106,222–225]. As a result, student pilots can opt to complete all required flight training hours in actual aircraft if they prefer, allowing them to either entirely bypass FSTD training or use it only partially. For example, major global civil aviation authorities, including the Federal Aviation Administration (FAA) in the USA, the Civil Aviation Authority (CAA) in the UK, the European Union Aviation Safety Agency (EASA), the Civil Aviation Administration of China (CAAC), and Transport Canada Civil Aviation (TCCA), provide optional FSTD allowances specifically for the Private Pilot License (PPL) and Commercial Pilot License (CPL)—the two common license types in GA[106,222–225]. The PPL is tailored for recreational flying, whereas the CPL enables pilots to undertake business-oriented activities within GA, such as emergency services, agricultural aviation, aerial photography, and other operations distinct from mainstream CAT. For PPL training, these authorities cap FSTD use at 5 hours. For CPL training, they allow broader FSTD utilization, with certain training pathways to obtain a CPL permitting over 30 hours, except TCCA, which limits FSTD use to 10 hours[106,222–225]. The persistent perception that FSTDs are less capable and cost-effective[198,201–203,220,221], along with regulatory flexibility, has led to their underutilization, thus preventing student pilots from fully exploiting the benefits of FSTD training.

Recent advancements in technology have drastically improved the capabilities of FSTDs while significantly reducing costs[95,198,220,221,226,227]. Despite these advancements, the general aviation community—flying schools, instructors, and student pilots—may lack awareness or familiarity with these improvements or remain skeptical about their effectiveness[198,202,217,226–234]. Conducting a user acceptance study in Canada, where FSTD use remains optional and less prevalent compared to other nations, could help determine if current perceptions align with modern FSTD capabilities, potentially uncovering new opportunities for cost-effective skill development.

In Canada, GA pilot training follows a traditional hours-based licensing framework that mandates varying flight training hour requirements for each license type, along with mandatory written exams and ground training[106]. While this approach is standardized, it tends to prioritize the accumulation of flight hours and overlooks the potential benefits of FSTDs, especially in emergency scenario training[109,128,200,201]. Furthermore, existing regulations do not mandate FSTD training, which aims to ease financial pressures on flying schools but perpetuates reliance on conventional in-aircraft training methods[109,128,200,201,235]. This hours-based approach stifles innovation in training methodologies, including the use of advanced simulation tools (FSTDs) that could enhance safety. Therefore, despite the longstanding integration of FSTDs across GA pilot training practices in Canada, their adoption has been slow and inconsistent[109,128,200,201,235]. At a critical juncture where Canada's GA sector grapples with integrating technological advancements into the pilot training framework, this study aims to move beyond

the mere question of adoption, focusing instead on the perceptual acceptance and barriers to FSTD use. It will particularly examine pilot attitudes towards using FSTDs for routine operations and emergency scenarios, and how these perspectives may influence the potential for broader implementation of FSTDs in GA pilot training. Understanding how pilots in the GA training landscape view the potential of FSTDs to enhance routine and emergency training can provide valuable insights for refining training curricula and developing effective implementation strategies. Additionally, this study will explore the potential of augmented reality (AR) technology, delivered through head-mounted display (HMD), as an assistive training tool in pilot training. Unlike FSTDs, AR is relatively novel in GA pilot training but shows strong potential for enhancing learning outcomes in education[236–241]. By investigating the use of HMD-based AR—technology that has yet to be widely studied or adopted in GA pilot training—this study adds value by evaluating whether pilots perceive this technology as beneficial and assessing its potential to meaningfully influence current GA training practices.

4.2 Related Work & Research Question

The current empirical research makes a modest contribution to exploring advanced technologies, such as FSTDs and AR, specifically within the domain of GA airplane pilot training. Notably, a study by Dennis and Harris in England involving 21 novice pilots highlighted the cost-effectiveness and educational benefits of low-fidelity FSTDs for ab initio pilot training[207]. Similarly, McLean et al. in Australia assessed the use of FSTD-based training in Private Pilot License (PPL) courses with 29 novice pilots, confirming substantial safety and risk-reduction advantages[211]. In Turkey, Beköz and Akteke's study of 8 flight instructors training PPL candidates revealed that initial FSTD training significantly enhanced operational abilities and confidence[206]. Schaffernak et al. in Austria examined 60 licensed pilots, affirming the utility of AR for enhancing various training aspects such as theoretical lessons, pre-flight inspections, and practical training[242]. Also in Austria, Moesl et al. investigated the use of AR applications in Type Rating courses, revealing that AR enhanced various training elements among 31 pilots and 22 instructors by complementing traditional methods[243]. In the United States, Thomas R. and Lynch T. assessed the effectiveness of various HMDs for ab-initio training, identifying models that can significantly improve knowledge transfer and realism perception[244]. Additionally, a study by Prayitno et al. involving 34 novice pilots in Indonesia found that hands-on FSTD training enhanced their proficiency and learning outcomes[212].

However, most of these studies largely focus on exploring the efficacy of FSTDs and AR but overlook how pilot attitudes and perceptions influence their adoption and implementation. The impact of pilot acceptance and perceptual barriers on the broader integration of FSTDs and the use of AR in GA pilot training remains significantly underexplored. This underscores an urgent need for research focused on understanding pilots' perceptions to uncover why FSTDs, despite their longstanding presence, have not

been fully embraced in GA pilot training, and to identify perceptual influences that could shape the use of emerging technology like AR, which is relatively new to the field of GA training. Additionally, the findings in these studies are constrained by small sample sizes and limited participant diversity, limiting the generalizability of the results across the GA community. Most research has concentrated on specific groups, such as novice pilots or flight instructors, offering valuable insights but failing to capture the broader spectrum of pilot experiences in GA, from student pilots to seasoned GA commercial aviators. A more comprehensive approach, gathering feedback from a wider array of participants, including those with various GA license types and rating qualifications, is essential to uncover the full range of factors influencing technology adoption in pilot training. Furthermore, Canada remains an under-researched area concerning the use of FSTDs and AR in GA pilot training. Studies examining how pilots' perceptions influence the broader adoption of FSTDs are conspicuously absent in Canada. Similarly, investigations into how pilot perceptions could facilitate or impede the use of emerging AR technology are also notably lacking.

To address the research gap, our study aims to gather insights from both student and licensed pilots in Canada's GA sector, ensuring diversity by including various license types and ratings. While our focus is on GA, perspectives from experienced commercial aviation pilots have also been incorporated to provide broader perspectives that GA training could greatly benefit from. By employing quantitative methods to assess pilot perceptions, our objective is to generate valuable findings that could potentially influence the advancement of technology-oriented pilot training methods. Given that our scope is specifically limited to airplane pilot training and the use of FSTD and HMD-based AR technology, we formulated the following research question to guide our investigation: 'Is there significant interest among student and licensed pilots in utilizing FSTDs and HMD-based AR technology for GA airplane pilot training?'

4.3 Method

4.3.1 Instrument

An internet-based survey was designed to gather student and licensed pilots' self-reported perceptions on using advanced technologies in GA pilot training, focusing on the use of FSTDs and HMD-based AR. The survey included four questions: three quantitative and one qualitative. The first question assessed perceptions of FSTD use for routine flight operations, while the second focused on FSTD use for emergency training. The third question explored the potential of using HMD-based AR technology to enhance learning. The qualitative question sought potential improvements in pilot training methods and technology. Demographic and professional details such as age, gender, education level, pilot licenses and ratings, and flight experience were also collected. The survey was not designed to evaluate training outcomes or validate

the effectiveness of FSTD and HMD-based AR technologies. Instead, it aimed to gather student and licensed pilots' perspectives on their utility as training tools, specifically assessing technological acceptance and how useful pilots believe these technologies can be for training purposes. It represents a perception-based exploratory study. Furthermore, the survey deliberately avoided categorizing questions by specific GA license certifications or ratings, encouraging a broad consideration of GA training and capturing a diverse range of experiences. This approach aimed to minimize potential biases associated with specialized license certifications or ratings. The four survey questions are outlined in Table 5.

Table 7. Survey questions to assess perceptions on using advanced technologies in GA

For questions 1-3, rate the statements using a 5-point Likert scale: 1 ('Strongly Disagree'), 2 ('Disagree'), 3 ('Neither Agree Nor Disagree'), 4 ('Agree'), and 5 ('Strongly Agree'). For question 4, please provide a descriptive response.	
1.	In context of the current flight training standards, increased use of flight simulation training devices (FSTD) can provide student pilots an opportunity to strengthen flight competencies and gain higher proficiency to manage routine (normal) flight operations; while also, creating potential for reduced training time and cost.
2.	Emergency or non-normal scenario training conducted in a FSTD could enable student pilots practice for surprise habituation and provide an opportunity to gain proficiency in handling unexpected or novel events.
3.	Assistive technology such as augmented reality (AR), delivered through head-mounted display (HMD), can enhance the real-world environment by superimposing digital information such as text, graphics, videos, or voiceovers directly onto operational spaces like the flight deck. This integration provides continuous access to essential data and instructional guidance. Despite limitations like cost or the need for usability training, such technology, when used for flight training in FSTDs, could create a dynamic and immersive environment with significant potential to improve learning.
4.	Briefly state any training, and technological improvements or methods that can improve instruction and assessment of the training standards and subsequently improve learning for student pilots.

To ensure participants were well-informed before starting the survey, a detailed information letter was provided alongside the survey. This letter was presented as the first item, offering key context for the initial three survey questions and helping participants understand and engage with the survey content. The letter clarified that the questions related to FSTDs and HMD-based AR technologies aimed to assess their roles as supplementary tools to traditional in-aircraft training methods, rather than as replacements. For the FSTD-related questions, participants were informed that, despite the variety of FSTD types, the focus was on gathering general impression of how any qualified FSTD could enhance proficiency in flying skills and contribute to improving learning for both routine operations and emergency procedures. For the HMD-based AR-related question, participants were informed that detailed information, including video demonstrations, would be provided to enhance understanding, particularly for those with limited prior experience with the technology.

A custom-made AR application was developed in collaboration with multiple Certified Flight Instructors (CFIs) to teach two flight procedures in an advanced flight simulator using the Microsoft HoloLens 2 (HMD): the 'Before-Takeoff' checklist and the 'Final Approach' landing. During the live survey, participants were introduced to the HMD setup through a demonstration video before addressing the HMD-based AR-related question. The video demonstrated how the HMD is worn by the student pilot, how virtual objects are projected into the student pilot's field of view, and how the HMD's head tracking ensures precise alignment of these virtual objects with the physical cockpit. This introduction was included to help survey participants understand that, with the AR-integrated HMD, student pilots can seamlessly operate physical cockpit controls while interacting with virtual objects. Following this introductory demonstration, participants watched two separate 10-minute videos, one for each flight procedure. These videos, filmed from the HMD's field of view, showcased a student pilot performing the 'Before-Takeoff' checklist and the 'Final Approach' landing procedures. The videos demonstrated how AR, through real-time visual objects integrated into the cockpit's operational space, could reinforce flight procedures by offering step-by-step interactive guidance, allowing student pilots to practice and refine each step within the procedures through self-paced lessons designed by the CFI. Participants were only observers of these video demonstrations, and their understanding of AR's role in training was supported by an open channel for communication, where they were invited to contact the researcher with any questions.

Figure 9 depicts a student pilot using an AR-integrated HoloLens 2 to practice a flight procedure within a simulator. This figure also includes a snapshot from the 'Before-Takeoff' checklist video, showcasing a real-time AR instruction cue that prompts the student pilot to set the strobe lights as part of the procedure. The intent of these demonstrations was to showcase realistic introductory training scenarios to participants, highlighting the potential of HMD-based AR technology to enhance pilot training. Although various FSTDs exist, the video demonstrations specifically utilized the ALSIM AL250 simulator. Furthermore, it was noted to participants that the content delivery performance of AR may vary based on factors such as instructional styles, graphic design choices, and interaction methods like gesture recognition or voice commands. They were also clarified that the AR survey question was designed to gather preliminary data on the utility of HMD-based AR technology for enhancing learning, with assessments based on participants' engagement with the video content or their prior knowledge.



Figure 9: Student pilot using AR-integrated HMD in a flight simulator (left) and a snapshot from 'Before-Takeoff' checklist video showing a real-time AR instructional cue to set strobe lights (right)

The use of the survey as a research instrument and the design of its questions, including the collection of demographic data and the incorporation of video demonstrations to facilitate the understanding of a new technology in educational contexts, are based on established civil aviation research frameworks from published literature[142,154–158,160,161,164,175,176,243]. This confirms their suitability for the intended research, aligns with methods used in preliminary exploratory studies, and supports the feasibility of conducting reliable research using a limited set of Likert scale questions. Since the survey was designed to capture broad insights rather than to measure specific constructs, traditional statistical reliability testing was not required[166–169]. To enhance the survey's effectiveness and ensure it met its research objectives, a comprehensive pre-testing was conducted with a selected group of CFIs, student and licensed pilots. Their feedback was instrumental in refining the survey's wording, structure, and content, ensuring that the questions were clear, neutral, and relevant to the target audience. This process helped identify areas for improvement by reducing ambiguity and enhancing clarity, while also validating the survey's relevance and appropriateness. Through this iterative refinement, the survey was strengthened to effectively gather reliable, meaningful data and accurately capture the intended insights.

4.3.2 Procedure

The survey, conducted on the Qualtrics platform over a three-month period, targeted student and licensed pilots across Canada's GA and CAT sectors and was distributed through our partner flying schools. To ensure the participants were legitimate student or licensed pilots, we leveraged the existing identity verification processes used by these flying schools. Specifically, the schools were asked to distribute the survey exclusively to their active members, which included current students and licensed pilots employed as staff or affiliated with the institution. As flying schools already verify the identity of individuals before enrolling them as students, hiring them as staff or signing them up as members, we effectively utilized this

process to validate participants. Additionally, to further confirm participants' association with their respective flying schools, survey respondents were required to provide their flight school email address, which was anonymized during data processing to ensure confidentiality. This information was cross-checked to verify their standing and other demographic information with the flight school and prevent misrepresentation. These combined verification measures ensured that only legitimate student or licensed pilots participated in the study, reinforcing the reliability and accuracy of the participant pool.

Participants received an information letter explaining the study's purpose, their rights and responsibilities, and were provided context to understand the survey questions. An informed consent was obtained from all participants before survey questions were presented. This study was approved by the University of Waterloo's Research Ethics Board (#45717), with the study design and method executed in accordance with the board's published guidelines and regulations. We performed a thorough data cleaning process to remove incomplete or inconsistent survey responses, excluding 9 submissions due to missing data, resulting in 197 valid responses. The valid survey data was then further refined by correcting typographical errors and converting text variables into numerical values, ensuring the dataset's integrity and reliability. Quantitative analysis was conducted using IBM SPSS® 29, employing both descriptive and inferential statistics. Open-ended responses were vetted to remove irrelevant content and analyzed thematically, ensuring respondent anonymity and confidentiality as per ethical standards.

4.4 Results

The survey received 197 responses, divided between student and licensed pilots. The percentage distribution between student and licensed pilots, along with the breakdown of license types among licensed pilots, is illustrated in Figure 2. The license types include Private Pilot License (PPL), Commercial Pilot License (CPL), Integrated Airline Transport Pilot License (IATPL), and Airline Transport Pilot License (ATPL). Similarly, the gender distribution and education levels of these participants are outlined in Table 1. Participant ages ranged from 17 to 65, averaging 28.3 years with a standard deviation of 10.8. Pilots' flying hours showed a wide range, averaging 1616.4 hours with a standard deviation of 2811.4. Specializations varied with license type: PPL holders had Night Ratings, while CPL and IATPL holders shared a broader range of specializations, similar to ATPL holders who had the most extensive skills, including Instructor, Multi-Engine, Instrument, Seaplane, Night, and various Type Ratings.

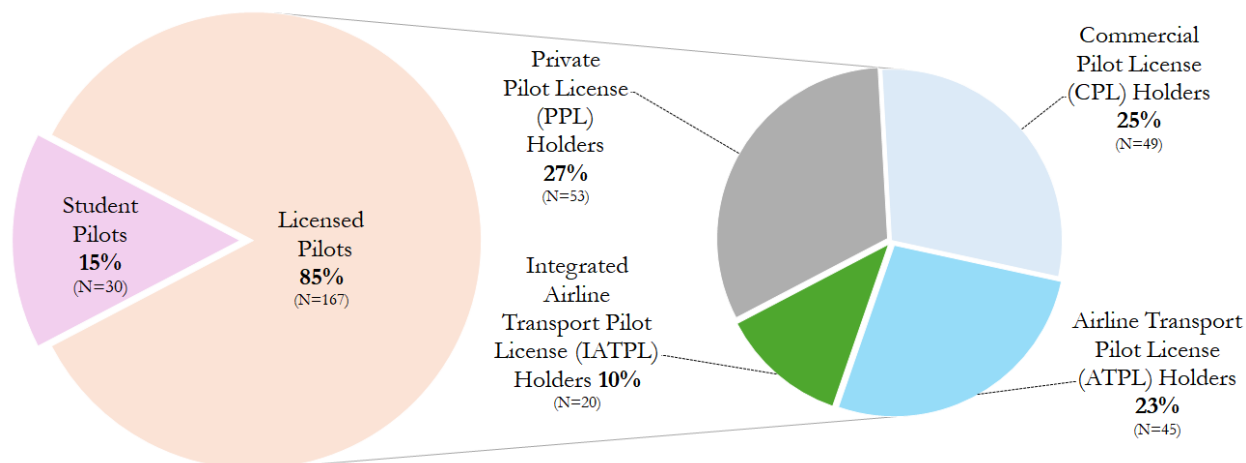


Figure 10. Percentage distribution of student and licensed pilots, including breakdown by license types

Table 8. Gender distribution and education levels of survey participants

Gender distribution	Male	73.1%
	Female	25.9%
	Non-binary	1%
Education level	High school diploma	32.9%
	Bachelor's degree or professional diploma	58.5%
	Advanced Degree	8.6%

Statistical techniques, both descriptive and inferential, were utilized to analyze perceptions of student and licensed pilot based on their responses to the Likert scale questions. The scale categorized responses as 1 ('Strongly Disagree'), 2 ('Disagree'), 3 ('Neither Agree nor Disagree'), 4 ('Agree'), and 5 ('Strongly Agree').

Firstly, a strong consensus was evident on the use of FSTDs for routine flight operation training, with an overall mean score of 4.07 and a standard deviation of 0.82, as illustrated in the histogram in Figure 3. Analysis by pilot experience level also indicated broad agreement: ATPL (Mean = 4.04, SD = 0.13), IATPL (Mean = 4.05, SD = 0.15), CPL (Mean = 3.97, SD = 0.13), PPL (Mean = 4.07, SD = 0.10), and Student Pilots (Mean = 4.26, SD = 0.13). The Kruskal-Wallis test, necessitated by non-normal data distribution (Shapiro-Wilk test) and insufficient sample size for transformation[180,183,182], confirmed uniformity across these groups. It showed no significant differences in perceptions ($H(4) = 2.68$, $p = 0.61$), with all pairwise comparisons indicating consistent views, showing consistently high adjusted significance values at 1.00.

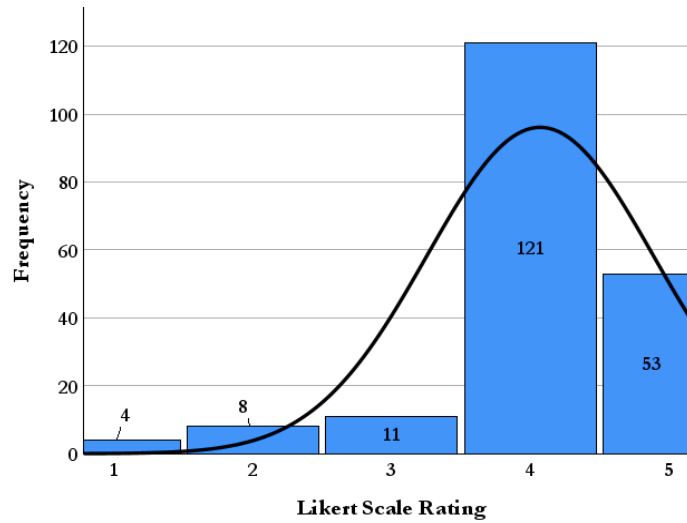


Figure 11. Survey responses on FSTD utility for routine flight operation training

Similarly, FSTD use for emergency or non-normal scenario training also indicated widespread agreement, with a high overall mean score of 4.37 and a standard deviation of 0.63, as illustrated in the histogram in Figure 4. Analysis by pilot experience level also showed consistent agreement: ATPL (Mean = 4.22, SD = 0.12), IATPL (Mean = 4.25, SD = 0.09), CPL (Mean = 4.42, SD = 0.07), PPL (Mean = 4.35, SD = 0.08), and Student Pilots (Mean = 4.60, SD = 0.10) showing the strongest support. The Kruskal-Wallis test ($H(4) = 7.58, p = 0.10$) indicated no significant differences in opinions across these groups. Pairwise comparisons were consistent, with all adjusted significance values exceeding 0.18, indicating no significant disparities. This non-parametric test was also chosen due to non-normal data distribution and a limited sample size[180,183,182].

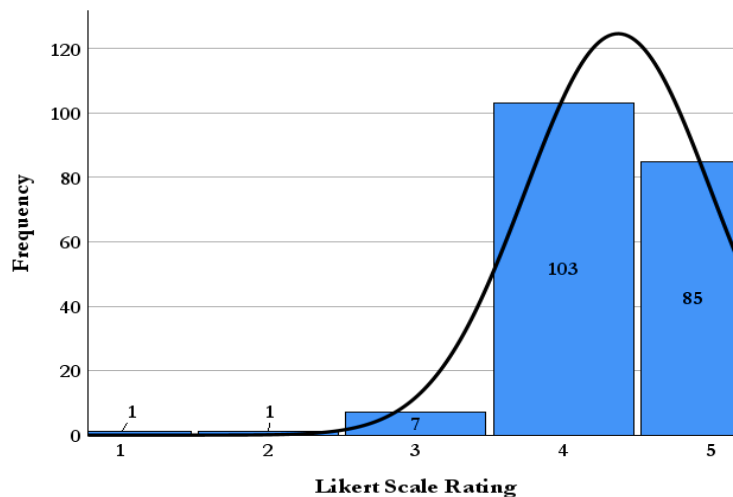


Figure 12. Survey responses on FSTD utility for emergency training

Lastly, the possibility of integrating HMD-based AR as an assistive training technology in pilot training was positively received by participants, with an overall mean score of 3.91 and a standard deviation of 0.77, as shown in the histogram in Figure 5. Analysis by pilot experience level revealed broad consensus: IATPL holders were most optimistic (Mean = 4.15, SD = 0.10), followed by ATPL (Mean = 3.91, SD = 0.11), CPL (Mean = 3.87, SD = 0.11), PPL (Mean = 3.84, SD = 0.12), and student pilots (Mean = 3.93, SD = 0.09). The Kruskal-Wallis test ($H(4) = 1.85$, $p = 0.76$), selected again due to non-normal data distribution and limited sample size[180,183,182], confirmed uniform perceptions across these groups, with no significant differences and all adjusted significance values at 1.00. Since the majority of participants (around 80%) viewed HMD-based AR as having the potential to enhance learning for student pilots, this underscores the need for further research to investigate its feasible integration within the GA pilot training framework.

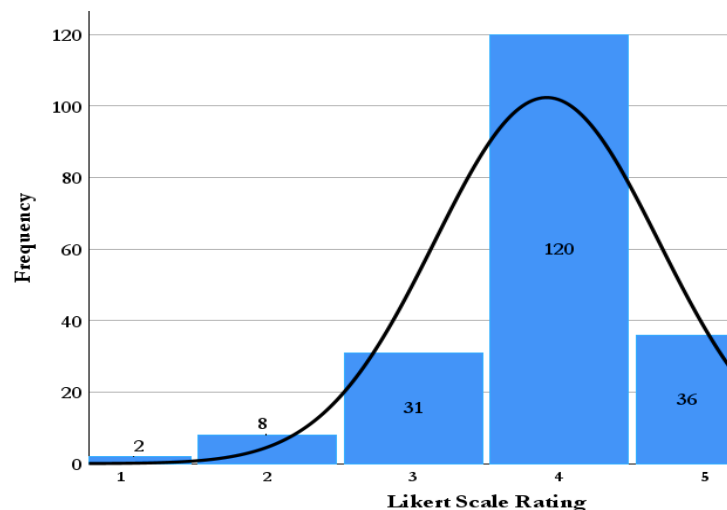


Figure 13. Survey responses on using HMD AR as assistive training technology

Responses to the open-ended qualitative question on potential improvements in pilot training methods and technologies were analyzed using thematic analysis according to Braun et al.'s (2017) methodology[245]. To ensure the reliability of the analysis, two researchers independently verified the responses using both deductive and inductive coding. Deductive coding was first employed to determine if the responses aligned with pre-existing categories derived from literature. These categories included Technological Integration[109,128,200,201,246–248], which focused on incorporating advanced tools such as FSTDs, virtual reality (VR), and AR to enhance training realism and safety; Pilot Learning Outcomes[95,206,208,209,211,226,240,249–251], which examined how these advanced tools can improve critical skills like procedural knowledge, decision-making, and situational awareness; Cost-Effectiveness

and Accessibility[198,203,209,211,220,226,252], which evaluated the affordability and scalability of adopting new training technologies; and Collaborative Learning and Instructor Roles[201,203,213,218], which explored how technology fosters collaborative learning environments and redefines the role of instructors. Subsequently, inductive coding was used to identify any emergent themes that were not previously considered. These included Technology Adoption Barriers, which highlighted challenges such as high costs and limited access to modern training tools; Pilot Adaptation to New Learning Methods, which addressed how pilots adjust to the integration of new technologies in training programs; and Personalized Training Needs, which reflected the demand for customized training solutions based on individual learning preferences and flight experience. This rigorous process led to the identification of three interconnected themes: “Innovative Technologies and Simulation in Pilot Training”, “Realistic and Practical Training Enhancements”, and “Collaborative and Experiential Learning Methods”. It should be emphasized that the findings discussed within these themes are based solely on participant feedback, not the authors' interpretations or perspectives.

The theme “Innovative Technologies and Simulation in Pilot Training” emphasizes embracing advanced tools and techniques in pilot training.

- Participants frequently expressed the value of integrating video recording with flight data monitoring to improve the learning experience in flight training, particularly during solo flights. As one participant noted, “You know, there’s no real way to check if we’re doing everything right when instructors aren’t around, especially in solo flights. Having video recordings with the flight data would really help me see where I messed up and fix things sooner”. Another echoed this sentiment, explaining how video recordings could allow instructors to provide more detailed feedback: “My instructor will be able to actually see where I messed up and break it down with me after, so I can learn and get better from there”. In line with this, another participant shared, “After solo flights, we do a debrief with the instructor, but it’s pretty much up to me to say what I thought went well or not. It’s hard to be completely sure if I’m giving an accurate picture, since there’s no formal system to track my performance. A more structured way to assess how I did would really help me improve faster”. This feedback highlights the need for integrating video recording and flight data monitoring to gain real-time insights into student performance, especially during solo flights. Such an approach could pave the way for more personalized training solutions, including partnerships with aviation analytics firms to provide students with effective, tailored feedback.
- Participants emphasized the growing role of home simulators, especially in regions with frequent weather disruptions. One participant explained, “The weather in Canada really messes with flight training. Sometimes there’s a gap of days or even weeks between lessons, and that slows everything

down. Having a VR simulator at home can be a huge advantage because I could practice during those breaks so I don't forget what I've learned". Others echoed the utility of home simulators for procedural reinforcement, as summarized by one participant: "For me, getting that extra practice with home simulators to go over different procedures would really help reinforce what I am learning in flight training and make me feel more confident". This demonstrates the strong interest in using home-based simulators to maintain or enhance procedural skills safely and cost-effectively. When integrated into formal training with clear guidelines, these tools not only have the potential to improve proficiency but also offer an affordable and flexible learning method.

- Participants widely supported self-paced online ground training, featuring interactive and up-to-date content. Many saw potential in this approach, as one participant commented, "Self-paced modules where I can dig into topics I struggle with would help me a lot more than just sitting through classes at a set pace". Another participant added, "Some of us pick things up faster, while others need more time with certain topics. Self-paced modules would let me focus on what I struggle with, instead of being forced to move at the same pace as everyone else". These programs can meet individual learning needs while maintaining compliance with aviation standards, offering a flexible and effective way to teach the required knowledge areas. Moreover, the inclusion of Video Preparatory Ground Instructions (PGIs) in an inverted classroom model was also supported by participants as a means to optimize classroom time. One participant summarized, "If I could watch theory videos at home and then just focus on practical stuff in class, it would make training way more efficient". This method could blend theory and practical learning, allowing more time for hands-on skill development in the classroom.
- Participants recognized high-quality simulators as essential for boosting training efficiency, safety, and proficiency. One participant with extensive instructing experience shared, "I'm a huge believer in simulators. They let us go through emergency situations, like engine failures or single-engine overshoots that would be way too risky to try in a real airplane. Back in the days, I used to do an exercise where I'd cut the fuel mid-flight to force a landing. Students were always shocked by how well the airplane glided with the prop stopped. You can't do stuff like that anymore, but simulators make it possible to practice these scenarios safely". Another participant with extensive experience in using advanced simulators added, "I've worked as an instructor in Level D sims for years, and the kind of training you can do in there, especially for procedures, is just incredible". However, concerns were raised about the quality of simulators at flying schools. One participant noted, "Most of the sims at flight schools just aren't up to par, so they're not really helpful for training. If schools invested in better, more advanced simulators, it would make a huge difference in how effective the

training is”. Reflecting on older simulator models, another participant commented, “When I was learning in the late 90s, we used simulators that were built in the 70s or 80s, and they were seriously outdated. Considering how much I value long-distance flying, dealing with changing weather conditions, and different airspaces and procedures, modern simulators could really give student pilots that experience safely. But those sims need to be high quality—not the outdated junk I had to use back then”.

- Participants also highlighted the need to address repetitive route flying by leveraging advanced tracking and data analytics. One participant stated, “Flying the same routes over and over doesn’t help us as much. But if we could leverage GPS tracking technology and data to experience different flying conditions, like mountainous terrain or busy airspaces, it would really make our training more comprehensive”. Another agreed, adding, “Flying the same routes over and over can really mess with your ability to handle different situations. Like, I can land just fine in calm weather or at a quiet airport, but throw in a busy airport or bad weather, and it’s a whole different game. Instructors might point out what you’re doing wrong in circuits or takeoffs, but that doesn’t mean you’re actually learning how to make decisions on your own. You end up depending on them too much instead of building the skills to think and react independently”. These insights reflect a growing recognition that varied routes and conditions, supported by advanced tracking and analytics, could broaden pilots’ exposure to diverse flying environments, ultimately improving adaptability and decision-making.
- The integration of AR/VR technology into ground training modules was seen as a promising approach to create immersive learning experiences that can enhance concept comprehension and retention, ultimately boosting student pilots’ readiness for operational flight settings. One participant shared, “With VR, you can sit in a virtual cockpit and practice all kinds of things, like how to handle engine failures or electrical system malfunctions, without the stress of being in the air. You can also go through different navigation scenarios, like using charts or GPS to plan a route, or see how weather conditions can change mid-flight and impact your decisions. It’s a great way to build up skills and get comfortable with things like radio communications and emergency procedures, all in a low-pressure environment”. Another participant noted, “With AR, you could see flight instruments and navigation data right in front of you during ground training, practicing real-time adjustments like altitudes or course corrections without leaving the ground. You could also do pre-flight inspections on a virtual plane, spotting issues before ever stepping into a real aircraft. It’d be a huge help for learning safety checks”.

The theme “Realistic and Practical Training Enhancements” focuses on replicating authentic aviation scenarios to better prepare pilots for real-world conditions.

- Many participants highlighted the importance of integrating scenario-based Air Traffic Control (ATC) exercises into flight training. One participant remarked, “We need more practice with real ATC communications while practicing circuits. It’s one thing to know standard operating procedures (SOPs), but real-world interactions make all the difference”. Another participant expressed a similar sentiment, saying, “The current practices feel outdated, especially with the types of exercises being tested. We need more scenario-based assessments where we’re given a situation with various threats, and we have to assess the variables and come up with a plan. That would do a lot more for developing real problem-solving skills than just focusing on specific flight procedures”. Introducing these scenario-based practices can greatly enhance students’ understanding of SOPs and improve their ATC communication, ultimately boosting situational awareness and radio communication skills. Collaborating with ATC professionals to develop these training scenarios could provide student pilots with more realistic and effective preparation for real-world operations. Additionally, a large number of participants also voiced strong support for integrating more scenario-based training through simulations. One shared, “We need exposure to more realistic simulation training where we’re thrown into emergencies like engine failures, onboard fires, or sudden changes in Instrument Meteorological Conditions (IMC). It’s one thing to know the procedures, but being able to apply them in a simulated scenario could improve our decision-making and situational awareness”.
- Several participants advocated for incorporating a dedicated module on flight control mechanics to deepen students’ understanding of how aircraft respond to control inputs, further enhancing practical knowledge. One participant shared, “Right now, flight training is all about executing practical maneuvers and responding to standard situations, but we don’t really get into the nitty-gritty of how the flight controls actually affect the aircraft’s behavior. I think we need more focus on the mechanics behind the controls, so we understand why the plane moves the way it does when we make adjustments”. Another added, “If we had a module that went beyond just the basics of drag and lift and really dug into how control inputs change the aircraft’s motion and orientation, it would make a huge difference. It’s not about getting into aerobatics, but developing a deeper understanding of how our actions directly impact the flight dynamics would make us much better pilots”. These insights underscore an opportunity for flying schools to collaborate with aviation specialists and engineers to develop specialized training resources and simulations that accurately depict the workings of flight controls. This collaboration could lead to the creation of interactive

and visually compelling educational tools, such as AR simulations, that allow students to explore and understand the effects of varying control inputs on aircraft behavior in real time.

- Many participants strongly recommended increasing the use of FSTDs for GA licenses and ratings in Canada. One participant noted, “Simulation training should be part of the curriculum. Right now, instructors tend to favor real flights because it helps with billable hours and logbook entries, but that means we’re not using FSTDs as much as we should. FSTDs are perfect for training in more complex or rare situations, and we’re missing out on that”. Another participant echoed this sentiment, adding, “Making FSTD time compulsory would give us a more well-rounded training experience. It’s not just about logging flight hours; it’s about building the skills we need to handle a variety of flying conditions safely. Instructors and students both need to realize how valuable FSTDs are for becoming better, more prepared pilots”. This feedback highlights the need for a more balanced and effective training approach, and have the potential to not only improve safety but also make training more comprehensive, better preparing pilots for the complex situations they may encounter in real-world aviation.

The theme “Collaborative and Experiential Learning Methods” promotes observational learning and teamwork.

- A number of participants suggested having more opportunities to observe experienced pilots during the flight training process, with one explaining, “I’d love to sit in the jump seat on real flights, not just instructional ones, to see how things are done when it’s not a lesson”. In contemporary flight training, a predominant focus on active flying often overshadows opportunities for student pilots to engage in observational learning practices. To enrich their training experience, these findings imply that seasoned pilots or instructors, particularly those of higher rank, extend invitations to student pilots to accompany them as observers on non-instructional flights, such as leisure or log-building trips. This arrangement can provide a relaxed environment for students to watch and glean insights from the Pilot-in-Command (PIC), mirroring the learning experience of a second officer in the jumpseat. This type of experiential learning can be invaluable for grasping the nuances of practical flight dynamics, decision-making strategies, and effective cockpit management.
- Participants also expressed a strong interest in team-based exercises, as reflected in the comment: “Team flying where we switch roles, like co-pilot, would help us understand the bigger picture and how to work together”. Based on this feedback, it is recommended that student pilots, pursuing GA license certifications for business-oriented activities, engage in team flying activities to strengthen their familiarity with SOPs and collaborative decision-making skills. In these sessions, students can alternate roles, including serving as the PIC or taking on supportive duties. This approach can

deepen their understanding of flight responsibilities while enhancing critical teamwork and communication skills.

- Flying schools can be encouraged to develop structured programs with clear learning objectives and thorough post-flight debriefings to maximize the benefits of these proposed observational and collaborative methods, which can consequently foster a more engaging and experiential learning environment.

4.5 Discussion

4.5.1 Perspectives on Using FSTDs, HMD-based AR technology, and Innovative Training Methods

This study compellingly supports the willingness to use FSTDs and HMD-based AR technology as complementary training tools alongside traditional in-aircraft training for GA pilot education. Quantitative data show a broad agreement among student and licensed pilots on the use of FSTDs to enhance routine flight operations and improve emergency response skills. Similarly, there was consensus on acknowledging HMD-based AR as an assistive training technology. Among various qualitative insights, the potential of these technologies in real-world training scenarios was notably emphasized also. These qualitative insights uncovered participants' transformative, forward-looking mindset, characterized by a strong interest in maximizing FSTD usage, the inclusion of high-quality simulators in flying schools, and the adoption of immersive AR-powered training solutions. This perspective reflects a proactive embrace of advanced technologies, such as FSTDs and HMD-based AR technology, highlighting participants' desire to strive for technical excellence and their readiness to meet the demands of modern aviation challenges.

The emergence of three distinct themes from qualitative insights, “Innovative Technologies and Simulation in Pilot Training”, “Realistic and Practical Training Enhancements”, and “Collaborative and Experiential Learning Methods” underscores a strong preference for merging technological innovations with hands-on learning to improve educational outcomes. Recommendations to adopt video recording with flight data monitoring during solo flights, home simulators, customized digital programs, and AR/VR technologies suggest a keen interest towards personalized and immersive learning experiences. Additionally, leveraging advanced tracking and data analytics to create varied flight conditions can support the development of enhanced adaptability and decision-making skills. Furthermore, the inverted classroom model shifts teaching methods to prioritize active, hands-on engagement over traditional lectures, with the potential to foster deeper and more effective learning. Realistic training enhancements, such as ATC scenario-based exercises, aim to closely replicate real-world aviation situations, bridging the gap between theoretical knowledge and practical application. This approach can sharpen students' situational awareness, critical

thinking, and teamwork—skills essential for managing the complexities of the aviation environment. Additionally, the proposed module on flight control mechanics emphasizes a more practical understanding of how aircraft respond to pilot inputs, which could equip pilots to better manage and anticipate flight dynamics across different scenarios. Collaborative and experiential learning, through observational exercises and group flying, can create a dynamic and interactive environment, encouraging teamwork and hands-on learning. By promoting teamwork and practical observation, these methods can deepen pilots' understanding of flight responsibilities and real-world aviation dynamics, which are critical for developing well-rounded skills. Collectively, these findings provide a comprehensive perspective on potential training enhancements for GA, offering valuable insights for regulatory authorities, educators, and other industry stakeholders to refine GA pilot training and maintain high competency standards.

4.5.2 FSTD integration into the Canadian GA Pilot Training Framework

Policy implications arising from the findings on FSTD use suggest that aviation training standards and regulations in the Canadian GA sector could benefit from placing greater emphasis on the utilization of FSTDs. Although TCCA's flight training regulatory requirements for GA pilot licensing are generally comparable to those of other major civil aviation authorities (FAA, CAA, EASA, and CAAC), its allowances for incorporating optional FSTD-based training into these requirements remain notably lower[106,222–225]. This disparity suggests potential to enhance FSTD utility in the Canadian GA sector by revisiting standards to consider expanded allowances for FSTD-based training hours across applicable GA licenses and ratings. Such changes could better align Canada's GA FSTD-based training practices with global standards, providing both student pilots and flying schools the opportunity to benefit from the cost and safety advantages of FSTDs. To drive this shift, regulatory authorities can build on existing research[206–212] that demonstrates the benefits of FSTDs and conduct deeper scientific assessments to explore how expanded FSTD use can effectively complement in-aircraft training within the Canadian GA context. A critical area for these assessments would be determining whether one hour of FSTD training can serve as an equivalent substitute for an hour of in-aircraft training, or if multiple FSTD hours are required to achieve similar learning outcomes. Identifying the optimal balance between FSTD-based allowances and in-aircraft training will be essential to fully realizing the advantages of FSTDs while maintaining high training quality and safety standards.

Flying schools will also need to adapt their curricula to integrate expanded FSTD-based learning and invest in certified devices that meet current regulatory requirements. For schools operating with outdated FSTDs, upgrades to achieve certification compliance will also be necessary. Recognizing the financial challenges associated with these changes, regulatory authorities could consider implementing support mechanisms to facilitate the transition. Potential measures could include increased funding for GA safety initiatives,

subsidies to offset FSTD acquisition costs, or tax incentives to encourage investment in training infrastructure. These efforts would particularly benefit smaller flying schools and promote equitable adoption of FSTDs across the GA training sector.

By prioritizing the expansion of FSTD use, Canada's GA pilot training programs can align more closely with the International Civil Aviation Organization's (ICAO) recommendations to adopt innovative and cost-effective training methodologies[247,248]. Ultimately, such advancements would enhance pilot preparedness for real-world challenges, strengthening the overall quality and safety of Canada's GA training ecosystem.

4.5.3 Potential for FSTD Adoption through Market-Driven Opportunities

Over the past decade, technological advancements have significantly improved the quality, functionality, and affordability of FSTDs[95,198,220,221,226,227]. Once prohibitively expensive, high-fidelity FSTDs are now much more accessible, offering highly realistic and immersive training environments at significantly reduced costs. This progress presents an opportunity for voluntary, market-driven adoption of FSTDs rather than relying solely on regulatory reforms. While existing regulations in Canada do not mandate FSTD use in GA pilot training, the findings of this study highlight the significant potential for increased adoption driven by market forces.

With entry-level FSTDs costing as low as \$10,000 USD, affordability has the potential to lower barriers to adoption[203,206–212,226,227,252], making it possible for even smaller flying schools to integrate FSTDs into their training programs. This can enable flying schools to strategically leverage FSTDs to differentiate themselves in a competitive market by offering enhanced training options that complement in-aircraft training, incorporating FSTDs for routine maneuvers and emergency scenarios. Such programs can attract student pilots seeking innovative, cost-effective ways to enhance their skills. Similarly, small businesses or individual student pilots could benefit from affordable FSTD options by establishing rental services or acquiring personal devices for supplemental practice outside regulatory requirements.

Fostering a culture of voluntary adoption supports innovation and choice within the training ecosystem and does not preclude future regulatory updates. By promoting the proven benefits of FSTDs, market-driven adoption can naturally increase utilization over time, enabling flying schools to balance the advantages of FSTDs with traditional flight training. This gradual, market-oriented shift can allow training practices to evolve organically through demonstrated effectiveness and economic incentives.

However, despite the latest technological advancements offering enhanced capabilities, FSTDs still face limitations in replicating certain flight tasks and experiences. Future research could focus on identifying specific maneuvers, procedures, or emergency scenarios that are most suitable for training on low-cost

FSTDs. This validation can help ensure that the most relevant aspects of pilot training are recommended for FSTD-based practice, while essential flight training requiring real-world experience continues to be conducted in an actual aircraft. By achieving this balance, low-cost FSTDs can be fully utilized as complementary tools to traditional flight training, enhancing training quality and safety without compromising overall effectiveness.

4.5.4 Benefits of FSTDs in the Canadian GA Landscape

The broad implementation of FSTDs could significantly improve the Canadian GA pilot training landscape by addressing several ongoing challenges.

Current GA pilot training requirements treat FSTD training as optional, which leads instructors to prioritize actual flight hours due to their contribution to billable and logbook hours[106,109,128,201]. This preference results in the underutilization of FSTDs, especially for complex, emergency, or high-risk scenarios that cannot be safely replicated in actual flights. Consequently, student pilots, influenced by the thrill of real flying and instructor preferences, often overlook the benefits of FSTD-based training. The inclusion of expanded allowances for FSTD-based training could allow for comprehensive Threat and Error Management (TEM) and Crew Resource Management (CRM) training. TEM training develops a pilot's ability to identify and manage potential threats, like adverse weather and equipment malfunctions, and errors that could jeopardize flight safety. CRM training focuses on enhancing interpersonal and communication skills necessary for effective teamwork under stressful conditions. FSTDs are uniquely suited for these types of training because they can simulate a wide range of realistic scenarios, enabling pilots to practice decision-making, situational awareness, and corrective actions without the risks of real flight. This can allow student pilots to anticipate problems and become adept for effectively managing real-world flight operations, enhancing safety and preparedness. Furthermore, weather significantly impacts flight training in Canada, often delaying the completion of programs[201,253,254]. Cancelled flying lessons due to adverse weather disrupt training continuity, extending the overall training period. However, FSTDs provide a valuable alternative, allowing students to continue practicing and refining their flight skills during unfavorable weather conditions, potentially resuming actual flight training without significant setbacks once conditions improve. Additionally, the diverse geographical and environmental characteristics of Canada's regions influence the training environment[201,255]. For example, the expansive farmlands of the Prairie Provinces provide numerous safe landing options, making training exercises easier compared to the mountainous regions of British Columbia[201], where rugged terrain increases the difficulty of maneuvers. Implementing scenario-based training with FSTDs that includes diverse landscape scenarios can help student pilots prepare for a range of conditions, enhancing their adaptability and skills.

Flight training also poses a significant financial challenge for student pilots, particularly for those needing additional time to refine their flying skills[109,201,256]. FSTDs offer a cost-effective alternative to actual aircraft, allowing for extended training sessions at a lower hourly rate. This affordability enables students to practice critical skills repeatedly without financial strain, such as mastering complex maneuvers like crosswind landings by repositioning directly to final approach, enhancing training efficiency. The reduced cost of using FSTDs can significantly lower the overall expense of flight training, aiding students in progressing more effectively toward their pilot certification. Integrating FSTDs could substantially address the extended training periods that student pilots currently experience before reaching the proficiency needed for flight tests. Presently, student pilots often require an average 65 hours of flight time to qualify for the PPL flight test, significantly exceeding the regulatory minimum of 45 hours[69–72,200]. By incorporating FSTDs into training programs, students could achieve proficiency more rapidly through repeated practice, immediate feedback, and focused skill development. This integration would streamline the training process, reduce the total flight hours required, and ultimately decrease the financial burden on students while accelerating their progress toward key milestones. Moreover, GA flying schools in Canada often face resource limitations, including a scarcity of aircraft and infrastructure[109,201]. This shortage makes it challenging for aspiring pilots to book sufficient training time, a problem exacerbated by the limited number of flying schools, which often leads to overbooked schedules and restricted access to training aircraft. Consequently, student pilots frequently encounter delays in completing their license certifications, sometimes extending over few years. The infrequent flying opportunities force students to repeat exercises, resulting in inefficiencies in time and cost. FSTDs offer a practical solution to mitigate these issues by allowing students to maintain and enhance their skills, thus preventing skill degradation, even when access to actual aircraft is limited.

4.5.5 HMD-based AR technology integration into the Canadian GA Pilot Training Framework

Regulatory authorities could leverage the strong interest demonstrated by study participants in adopting HMD-based AR technology as an assistive training tool within the GA sector. However, this initial enthusiasm should be seen as preliminary, requiring thorough empirical validation. Future research should assess how HMD-based AR-integrated training fits into the broader structure of GA pilot training and its effectiveness relative to traditional methods. The initial step could involve conducting empirical studies that immerse student pilots in simulated training environments using HMD-based AR technology. These studies can assess its applicability, usability, and educational efficacy, with a particular focus on its capacity for facilitating independent training. This could involve experiments where student pilots use HMD-based AR devices for procedural tasks such as pre-flight checks and in-flight procedures, with built-in

instructional guidance, to compare learning outcomes with those of traditional instructor-led methods. Following successful validation, the next phase could involve pilot (operational) testing at selected flying schools to establish best practices and yield valuable insights into the practical aspects of deploying HMD-based AR, including necessary curricular adjustments, the feasibility of independent, student-led learning sessions, as well as determining the optimal number of HMD-based AR training hours required for student pilots to achieve proficiency. Data from these schools could then inform broader decisions and contribute to shaping training program curriculums based on empirical evidence. Regulatory compliance must also be ensured so that HMD-based AR technology meets all training standards and qualifications, which includes rigorous certification processes to validate the technology as a recognized instructional tool. Finally, to facilitate widespread adoption, it is advisable for regulatory authorities to consider support mechanisms such as subsidies or grants to help flying schools manage the initial costs of adopting HMD-based AR technology and revising training programs.

4.5.6 The Paradox of Effective but Unappealing Training Technologies

While the effectiveness of training technologies such as FSTDs and HMD-based AR technology is central to their adoption, the perceptions of these tools by primary end users, such as instructors, and student pilots, are equally critical in determining their successful integration into training programs. For example, while the practical advantages of FSTDs in terms of cost-effectiveness and safety are established[206–212], their adoption in Canadian GA training practices also hinges on psychological and social factors influencing user acceptance. Resistance to FSTD-based training, whether due to a lack of engagement or an inability to recognize long-term benefits, could hinder integration, even when the technology demonstrably enhances training outcomes. This creates a paradox: a method proven effective may remain underutilized if perceived negatively by its primary users[198,202,203,218,228,234]. Psychological and social factors, such as cognitive resistance to new learning tools, the need for sustained engagement, and adherence to established norms, can play a significant role in shaping adoption decisions[257–260]. For instance, student pilots who view FSTDs as less engaging or unnecessary may disengage, resulting in suboptimal outcomes. Similarly, instructors may deprioritize FSTDs if they perceive resistance from student pilots, further limiting integration. Bridging the gap between pedagogical utility and user acceptance is essential to unlocking the full potential of the technology being introduced.

This study investigates these perceptual barriers to understand their impact on the adoption of FSTDs and HMD-based AR technologies. By uncovering how these technologies are perceived, the research provides insights for regulatory authorities and the training industry to align pedagogical effectiveness with user engagement. Addressing this challenge requires a dual focus: promoting the utility of FSTDs and AR technologies while fostering an environment where their value is recognized by potential users. Strategies

such as awareness campaigns, incremental exposure, and evidence-based demonstrations of benefits can help resolve this paradox and drive broader acceptance within training programs. Incorporating feedback from both instructors and student pilots into curriculum design can further enhance the perceived value of these technologies. For example, features such as scenario-based training, gamification, and interactive elements can make FSTD-based learning more engaging and relatable. By addressing these psychological and social factors, this study underscores the importance of balancing user perspectives in technology adoption. While regulatory considerations and market-driven strategies play important roles, addressing human factors is critical for the successful integration of these technologies into the Canadian GA pilot training framework. Future research could explore these dynamics further, providing actionable insights to align the needs and expectations of end users with the proven benefits of FSTD- and AR-based training.

4.6 Limitations & Future work

Using online surveys limited our ability to ask follow-up questions or get immediate clarifications, leading to the removal of unclear qualitative data during data cleaning. Additionally, participants with a pre-existing interest in technology may introduce optimistic biases. Future research could benefit from a mixed-methods approach, combining qualitative methods like focus group discussions with quantitative surveys to achieve a more objective assessment of participant feedback. This would allow deeper exploration of participant motivations and help address potential biases.

The pre-survey exposure to HMD-based AR technology demonstrations via videos may influence participants' perceptions, risking opinions formed primarily on the video content. Future research could greatly benefit from allowing participants to interact directly with AR technologies. Such hands-on engagement can establish a more comprehensive understanding of user perceptions and the educational implications of AR technology in pilot training.

The study allowed for a broad capture of insights but did not differentiate between the unique training needs and focuses associated with various pilot license certifications and ratings within GA. Pilots pursuing different certification levels or specific ratings may have distinct training requirements, which could influence their perceptions of the utility of FSTDs and HMD-based AR technologies. For example, student pilots may view these technologies as essential for building foundational skills, while more experienced pilots could value their ability to simulate and instruct complex scenarios that are difficult to replicate in real flight conditions. Future research can investigate these differences, which can support the development of targeted training programs tailored to the specific needs of each pilot group.

While the study presents a promising outlook on integrating FSTDs and HMD-based AR technologies into GA pilot training, the sample size of 197 participants is relatively small. This group comprises 15.3%

student pilots and 84.7% certified pilots, indicating a skewed representation that may not fully capture the diversity of GA training. Caution is advised when interpreting the findings' broader applicability. Future research should increase the sample size and ensure a balanced representation of student and licensed pilots. Expanding the study to include participants from multiple countries could also provide a clearer understanding of these technologies' global relevance in GA pilot training.

While survey responses indicate interest in adopting technologies such as FSTDs and HMD-based AR, it is important to recognize that stated willingness does not guarantee actual adoption. In practice, several institutional and systemic gatekeepers—such as regulatory approvals, training culture, instructor acceptance, and financial limitations related to equipment procurement, maintenance, and instructor training—can significantly influence integration. As such, participant enthusiasm may reflect aspirational intent more than practical feasibility. The long-term adoption of these technologies will depend on overcoming these structural barriers. Future research should investigate these challenges through implementation-focused studies, including pilot program evaluations and interviews with key decision-makers (e.g., aviation regulators, flight school administrators) to assess the conditions necessary for sustainable and scalable integration.

Given the study's preliminary exploratory design, it was aimed at gathering initial data on the perceived utility and value of FSTD and HMD-based AR technology in GA pilot training, rather than providing definitive evidence of their technological effectiveness. Consequently, a single-group observation approach was used, lacking an independent variable such as a comparison group or a pre-post intervention design. This approach lays the foundation for more rigorous future research. Subsequent studies could refine these findings by implementing a more controlled setup, which could include a comparison group or employ a longitudinal design to validate the initial results derived from this study.

This study primarily focuses on the Canadian GA training framework, addressing specific opportunities and challenges within this context. However, flight training regulatory standards for GA pilot licensing under TCCA are broadly comparable to those of major civil aviation authorities, particularly in the West, though specific requirements and allowances may vary[106,223–225]. Consequently, this study's findings on GA student and licensed pilots' perceptions of FSTD use to enhance routine and emergency training, the potential of HMD-based AR technology as an assistive training tool—both serving as complementary training resources to traditional in-aircraft training—as well as qualitative perspectives into potential improvements in pilot training methods and technologies are likely relevant beyond the Canadian setting. These insights can potentially inform civil aviation regulatory authorities and the training industry in the West. Specifically, they may guide broader FSTD adoption without necessitating immediate regulatory intervention, encourage exploration of HMD-based AR technology in their GA contexts, and support

technological and best-practice advancements to enhance GA training. Although this study did not collect data from other countries, comparable standards and practices suggest similar outcomes may be expected in analogous contexts. Future research could validate these findings by collecting data from additional regions to confirm their broader applicability.

The use of direct evaluative language in certain survey questions may have shaped how participants framed their responses, potentially encouraging a more critical lens. While the intent was to encourage thoughtful reflection, such phrasing could influence participants to focus more on challenges or areas for improvement. Future research could benefit from incorporating more balanced question framing, combining evaluative and affirming language, to allow participants to reflect on both strengths and weaknesses in their training experience.

As with most perception-based studies, the findings presented here reflect participants' individual experiences and subjective viewpoints. The use of validated survey instruments lends robustness to the insights, yet it is important to acknowledge that these responses represent perceptions at a specific point in time, rather than direct behavioral outcomes. These results provide timely and meaningful perspectives on the current state of technology acceptance in general aviation training. Future research could extend this work by incorporating longitudinal or mixed method approaches to examine how perceptions shift with continued exposure, hands-on use, and broader adoption of simulator and AR technologies across different training environments.

4.7 Conclusion

This study highlights the untapped potential of FSTDs in Canada's GA sector, where they remain underutilized despite their longstanding adoption. The results indicate strong support for using FSTDs in both routine and emergency training contexts, emphasizing their ability to improve proficiency, safety, and cost-efficiency. These findings not only motivate expanded use but also provide valuable insights for refining the implementation of FSTDs in the GA pilot training framework, offering practical recommendations for broader adoption. Additionally, while AR is still emerging in the GA pilot training context, survey responses suggest a notable interest in its potential to enhance pilot training. However, further research and practical validation are needed to fully assess its effectiveness.

To maximize the benefits of advanced training technologies such as FSTDs and AR, the aviation training community must address both perceptual and regulatory barriers that currently limit broader adoption. Prioritizing strategic regulatory updates to standardize FSTD usage across GA pilot training programs and conducting empirical studies to validate AR's applicability and effectiveness, could be key next steps. Furthermore, financial assistance may be necessary to support smaller flying schools in adopting these

technologies. Future research could build on these preliminary findings to gain deeper insights and guide the GA pilot training industry in adopting technology-enhanced training solutions.

Chapter 5 (Study 4)

Evaluating Augmented Reality as an Assistive Training Tool for Ab Initio General Aviation Pilots: An Empirical Study in a Simulated Flight Environment

5.1 Introduction

General aviation (GA) pilot training has traditionally relied on instructor-led methods, where student pilots develop flight skills through one-on-one training. While widely adopted by aviation regulatory authorities to ensure consistency and compliance, it has seen limited integration of emerging training technologies, missing opportunities to enhance learning efficiency, reduce costs, and optimize training outcomes [1,2,4,5,261]. Although the general aviation industry has been slow to modernize its training methodologies, the growing emphasis on sustainability has highlighted existing inefficiencies, prompting discussions on the need for more efficient and environmentally responsible training approaches [5,262–265]. Extensive in-flight training requirements contribute to high fuel consumption, increased carbon emissions, and elevated training costs [3,266,267]. These challenges not only impose financial burdens on student pilots but also limit flight school capacity, as they often face constraints related to aircraft availability, airspace access, and instructor resources.

Despite the economic significance of aviation, industry stakeholders increasingly recognize the need to address its environmental impact, and GA is no exception [263]. The adoption of sustainable training practices aligns with broader industry efforts to mitigate climate change. Innovations such as fuel-efficient aircraft, electric aircraft, and alternative aviation fuels present promising solutions [3,268,269]. Additionally, the use of Flight Simulation Training Devices (FSTDs) and emerging immersive technologies, such as Virtual Reality (VR) and, Augmented Reality (AR) provide opportunities to reduce the reliance on in-flight training while enhancing learning effectiveness [270,271]. Among these digital innovations, AR has demonstrated significant potential in transforming educational experiences across various sectors, including military and defense, manufacturing, healthcare, general education, and technical fields such as maintenance and engineering. [26,27,272–277]. By seamlessly overlaying digital information onto real-world environments through wearable technologies, AR creates immersive mixed-reality experiences that enhance human information processing, facilitate skill development, and improve overall training efficiency [278,279]. Another key factor driving interest in AR-based training is the increasing availability and affordability of high-tech commercial off-the-shelf AR devices, making the technology more accessible [280,281]. However, despite its potential, AR adoption in aviation training, particularly in

GA pilot training, remains limited. Regulatory authorities have yet to fully recognize AR as a viable training tool, preventing flight schools from integrating it into their curricula. Additionally, pilot perceptions toward AR vary, with some expressing optimism about its potential to enhance learning and skill development, while others remain skeptical due to regulatory uncertainties and the industry's conservative stance on adopting new training technologies [2]. For AR technology to gain broader acceptance in GA training, there is a need for concrete, scientific evidence demonstrating its effectiveness. Therefore, this study aims to evaluate the potential of AR as an assistive training technology in pilot education, with a specific focus on general aviation training within the civil aviation sector. More specifically, it examines AR's role in ab initio training, where student pilots begin training with no prior flying experience, and assesses the effectiveness of AR technology delivered through Head-Mounted Display (HMD). By analyzing the impact of AR-assisted instruction on training outcomes and gaining deeper insights into how student pilots perceive and interact with this technology, this research seeks to provide empirical evidence supporting its potential integration into pilot training programs. Through this investigation, it contributes to the broader goal of fostering innovation, improving training efficiency, and advancing sustainability in pilot education by offering an engaging, cost-effective, and environmentally friendly alternative to conventional training methods.

5.2 Related Work

Augmented reality (AR) has broad applications across aerospace and other industries. This review focuses on AR's potential as an assistive technology to enhance pilot training, drawing from peer-reviewed journals and conference proceedings. The studies reviewed prioritize experimental research with robust data collection methods and assess outcomes using both objective and subjective measures in operationally relevant contexts. While the study itself focuses specifically on ab initio pilot training, the literature review takes a broader approach. It explores AR applications across all stages of pilot training, including advanced and specialized phases, to provide a comprehensive overview of AR's potential in pilot education. By including studies beyond ab initio training, this review highlights AR's general applicability and versatility, offers valuable insights that may indirectly inform early-stage training, and ensures significant findings from other training phases are considered.

Table 7 provides a comprehensive summary of key studies on AR applications in pilot training, capturing the breadth of the literature while highlighting diverse research efforts across various operational contexts. Building upon this overview, the following sections of this literature review examine the findings and insights drawn from the studies summarized in Table 7. The studies are laid out sequentially, covering AR's potential in task-specific training, decision-making in flight operations, ground training, and military or high-risk environments.

Table 9. Overview of AR-based research in pilot training

Publication	Environment	AR Device	AR Features	Test Scenario	Measured Outcomes
Schaffernak et al., 2021	Light aircraft simulator	Microsoft HoloLens (1st gen)	Displays flight parameters (airspeed, altitude) and flight path vector	Landing Approach with Power-Off Spot Landing	Kinematic Deviation Usability
Schaffernak et al., 2023					Perceived workload Situational awareness Emotional state Motivation
Alce et al., 2020	Virtual instrument panel created using AR	Microsoft HoloLens (1st gen)	Virtual instrument panel overlay displaying pre-takeoff flow patterns for structured instrument checks	Pre-takeoff flow pattern	Memory recall accuracy Perceived workload Usability
Li et al., 2020	Microsoft Flight Simulator X	Augmented Primary Flight Display (PFD) within Microsoft Flight Simulator X	Augmented visualization on the Primary Flight Display (PFD), highlighting activated flight modes using borders around airspeed, altitude, and heading indications	Instrument Landing System (ILS) landing with unexpected mode changes	Eye-tracking metrics Perceived workload
Li et al., 2022	High-fidelity Boeing 747 simulator	Microsoft HoloLens (1st gen)	Visual highlights, guiding arrows, and voice or gesture commands for pre-landing procedure	Pre-landing checklist	Perceived workload Situational awareness
Minaskan et al., 2021	Cockpit Procedures Trainer (high-fidelity Airbus A320 cockpit simulator)	Microsoft HoloLens 2	Visual and auditory guidance for situational awareness and decision support	Complex landing scenario involving multiple phases	Situational awareness Cognitive workload
Walko and Schuchardt, 2021	High-fidelity helicopter simulator	Microsoft HoloLens (1st gen)	Navigation markers and flight metrics (speed, altitude, and drift indicators)	Approach in degraded conditions	Perceived workload Situational awareness Usability
Tran et al., 2018	High-fidelity Airbus A320 simulator	Microsoft HoloLens (1st gen)	Visual guidance for engine fire management	Engine fire during cruise flight	Reaction Time Perceived workload Usability

Perez et al., 2019		Microsoft HoloLens (1st gen)	Spatial guidance, visual markers, and text instructions for checklist completion	After-takeoff, approach, and landing checklist under high-workload condition	Perceived workload Execution ease Success rate
Fuchter et al., 2020	AR-based mobile application	Smartphone	Life-size virtual flight panel displaying interactive checklist steps and visual cues.	Familiarization with flight panels and checklist training	Usability
Northrup et al., 2022	AR-based mobile application	Smartphone	AR overlays guiding ATC communication and checklist flows	ATC communication and checklist training	Communication accuracy Usability
Meister et al., 2022	Smartphone and tablet-based AR application	Smartphone or Tablet	Interactive 3D AR weather visualizations depicting thunderstorm lifecycle stages	Weather theory and hazards	Perceived workload Usability Knowledge gain
Kim et al., 2024	Desktop-based AR applicable	Smartphone	No-programming-required interface for creating interactive aviation weather training modules with 3D visualizations	Flight instructors developing AR-based modules to teach aviation weather concepts	Confidence in AR creation Perceived workload Usability
Arjoni et al., 2023	Robotic-based high-fidelity simulator	Microsoft HoloLens (1st gen)	Projection of a virtual leader aircraft	Formation flight training	Perceived workload Stress Performance
Aragon et al., 2005	High-fidelity rotorcraft flight simulator	Head-up display (HUD)	Visual hazard indicators showing airflow hazards	Landing on a moving ship deck	Crash rate Usability

AR has shown promising potential in developing specific flight skills, as evidenced by multiple studies. Schaffernak et al. trained three novice pilots on a landing approach maneuver in a light aircraft simulator, finding that AR improved landing skills, corroborated by both kinematic performance metric and self-reported usability ratings [280]. Extending this work, the researchers scaled their study to fourteen novice pilots, incorporating additional measures such as NASA-TLX for workload, SART for situational awareness, PANAS for emotional states, and QCM for motivation [282]. Interestingly, while the overall

performance differences between AR and non-AR groups were not statistically significant, AR presence and comfort strongly correlated with post-test improvements, inviting further inquiry into its potential. Similarly, Alce et al. used a virtual instrument panel created using AR for training twenty-seven commercial aviation student pilots on pre-takeoff flow pattern—a sequence of instrument checks across cockpit panels [278]. The study achieved 73% recall accuracy, paired with low workload scores (NASA-TLX) and high usability ratings (SUS), reinforcing AR's value for procedural training.

Li et al. explored AR's potential differently, using an augmented PFD in Microsoft Flight Simulator X with visual cues simulating AR without dedicated hardware. In a landing scenario, twenty pilots with varying levels of experience found the PFD effective in reducing workload, decreasing fixation durations, and improving attention to mode changes, as evidenced by NASA-TLX and eye-tracking metrics [283]. Building on this, Li evaluated AR-assisted landing configuration checks in a Boeing 747 simulator with thirty-four licensed pilots. The results revealed improved situational awareness (SART) and reduced workload (NASA-TLX), pointing to AR's potential in optimizing performance during critical flight phases [284].

Beyond task-specific training, AR's potential to enhance decision-making has also been studied. While these studies primarily focused on operational support under high-stress or high-workload conditions, they indirectly highlight AR's potential as a training tool.

Minaskan et al. studied AR's impact on decision-making during complex landing scenario with eighteen seasoned commercial pilots in a high-fidelity Airbus A320 cockpit simulator. The study demonstrated improved situational awareness and reduced cognitive workload, as measured by SART and NASA-TLX, supporting enhanced pilots' decision-making skills [23]. Similarly, Walko and Schuchardt examined an AR in-flight support system with five seasoned helicopter pilots in a high-fidelity helicopter simulator. The system, designed for improving safety during challenging maritime operations, provided real-time navigational tunnels and overlaid critical flight information. The outcome was clear: enhanced situational awareness, reduced workload and high usability ratings, supported by SART, NASA-TLX and SUS data—all contributing to greater safety and operational control for pilots [24].

Tran et al. expanded this investigation to emergency scenarios, involving twelve licensed commercial pilots in an engine fire simulation using a high-fidelity Airbus A320 simulator [25]. The findings were compelling: significantly reduced reaction times and lowered workloads (NASA-TLX), and high usability ratings (SUS), reinforcing AR's value in high-stress situations. Perez et al. added another dimension by focusing on procedural reliability. Their AR-based checklist assistant, tested with six airline pilots in an A320 simulator, targeted pre-landing procedure under high workload [285]. Participant feedback

highlighted the system's effectiveness in improving procedural accuracy and reducing errors, underscoring its potential to reduce pilot's workload and enhance reliability in critical phases of flight.

AR has also shown promise in foundational pilot training, including theoretical and classroom-based instruction. Fuctcher et al. and Northrup et al. conducted studies with unspecified novice pilots to assess smartphone-based AR training. Fuctcher et al. explored private pilot license (PPL) training aimed at familiarization with flight panels and engine start checklists, with participants finding the application realistic and beneficial, highlighting AR's potential for foundational skills development [286]. Similarly, Northrup et al. examined air traffic control (ATC) communication training, which participants found engaging and effective for enhancing essential communication skills [287].

Meister et al. expanded AR's application to weather education by evaluating a smartphone- and tablet-based AR tool designed to teach thunderstorm lifecycles and hazards [288]. Among six participants, including student pilots and instructors, the tool was praised for its realism and effectiveness in enhancing understanding. Positive outcomes on workload (NASA-TLX), usability (SUS), and knowledge gain assessments further highlighted AR's value in theoretical training. Kim et al. introduced another innovation: an AR authoring tool for flight instructors to create interactive ground training lessons [289]. Tested with forty-one participants, including instructors and pilots, the tool achieved high usability (SUS), low cognitive workload (NASA-TLX), and a notable 30% increase in confidence for AR content creation. Participants described it as intuitive, effective, and easy to integrate, highlighting its potential to transform ground training.

AR's role in military and high-risk flight environments has also been explored, particularly in enhancing operational safety and hazard recognition. These studies, while focused on high-stakes flight operations, also hint at AR's potential as a training tool for preparing pilots to navigate complex scenarios.

Arjoni et al. examined AR's application in military formation flight training with five novice pilots in a high-fidelity robotic simulator [21]. The system replaced the leader aircraft with a virtual projection, enabling pilots to practice maintaining alignment and proper distance. While effective for procedural learning, the system increased workload (NASA-TLX) and stress due to limitations in field of view and brightness, though performance was not significantly impacted. Similarly, Aragon et al. examined an AR airflow hazard visualization system with sixteen seasoned helicopter pilots conducting ship deck landings in a high-fidelity simulator [22]. By projecting hazard indicators within the cockpit view, the system provided an AR-like experience without requiring specialized hardware. The study reported a reduced crash rate and positive usability ratings based on post-simulation Likert scale questionnaires, further emphasizing AR's value in improving safety and operational performance.

While existing research demonstrates AR's value as an assistive training technology for pilots, significant gaps remain, particularly in-flight training contexts. Most studies have centered on commercial and military aviation, with experiments conducted in simulation environments tailored to these sectors. By contrast, general aviation—characterized by smaller, simpler aircraft with basic instruments—has seen little exploration. This gap is especially critical for ab initio training, where foundational skills are developed, as AR's potential for early-stage pilot training has been largely overlooked.

Research to date has often investigated AR's in-flight operational support, yet few studies have treated AR as a dedicated training tool. Even among these, the approach is fragmented, focusing on isolated flight phases (e.g., the final approach phase without touchdown) without accounting for the full procedural context, or narrowly addressing specific aspects of ground school topics. This piecemeal approach results in incomplete insights into AR's potential for integrated, end-to-end training lessons. Furthermore, studies rarely compare AR-based methods to traditional training in terms of knowledge retention or skill transfer to real-world contexts. The challenges don't stop there. Most research has prioritized experienced pilots, with minimal focus on novices. Even when novice pilots are included, sample sizes are often small or unspecified, limiting the generalizability of findings. Technological constraints further complicate the picture. Many studies rely on outdated HMDs or simulate AR-like experiences through projection systems rather than using AR hardware. These limitations dilute the immersive and transformative potential of AR, leaving questions about its true operational effectiveness unanswered. Design limitations are another hurdle. Static visualizations dominate AR systems in these studies, failing to account for the dynamic complexity of flight tasks. This diminishes their ability to enhance situational awareness or procedural understanding. Compounding the issue, some evaluations employ performance metrics misaligned with established human factors constructs, raising doubts about their reliability. Broader challenges also persist. Scaling AR tools for smaller GA flight schools and fostering collaborative learning environments—such as improving instructor-student interactions—remain underexplored. Even persistent issues like limited fields of view and poor hardware ergonomics, though acknowledged, have yet to be addressed. To fully realize AR's potential, these gaps and constraints demand systematic investigation.

In summary, while prior research has highlighted AR's potential in pilot training, significant gaps persist, particularly in its application to ab initio training within general aviation. This study seeks to address these gaps by focusing specifically on novice pilots with limited flight experience, ensuring alignment with the needs of early-stage training. Conducted in a simulation environment replicating smaller, simpler aircraft with basic instruments—such as single-engine planes commonly used in ab initio training programs—this research is tailored to the foundational context of GA pilot training. To overcome the fragmented focus of earlier studies, which often targeted isolated flight phases or narrow ground school topics, this study takes

a comprehensive approach. It examines end-to-end flight procedures within their full procedural context. By directly comparing AR-integrated HMDs with traditional paper-based training methods, the research evaluates the effectiveness of AR using validated human factors constructs, ensuring reliable and meaningful assessments. Most importantly, it also examines how skills learned in the AR environment transfer to simulated real-world scenarios, addressing a critical gap in prior research. The study employs a robust evaluation framework, incorporating post-study questionnaires, certified flight instructor assessments, and semi-structured participant interviews, to provide a holistic understanding of AR's training potential. Unlike static visualizations used in previous AR systems, this research introduces dynamic procedural guidance through HMDs, enhancing situational awareness and task interaction. Additionally, by emphasizing practical implementation and scalability, the study evaluates the feasibility of AR tools for GA flight schools, particularly their potential to enhance training efficiency, reduce reliance on instructor guidance, and support structured learning environments. By systematically addressing these limitations, this research provides empirical evidence to support the integration of AR technologies into ab initio pilot training, paving the way for more structured, scalable, and efficient training solutions within the general aviation sector.

5.3 Study Methodology

5.3.1 Materials

5.3.1.1 Flight Simulator

The study utilized a high-fidelity ALSIM AL250 flight simulator (Figure 14) housed at the Waterloo Institute for Sustainable Aeronautics (WISA) Simulator Lab at the University of Waterloo. This flight simulator was selected for its high fidelity and capabilities to replicate the operational environment of a generic single-engine aircraft, closely resembling the widely used Cessna 172—a standard in ab initio flight training. Its advanced avionics suite, realistic flight performance modeling, and immersive 250° by 49° panoramic visual field of view, projected through a VFR-VR-HD system, delivered an engaging and highly controlled simulation environment that closely mirrored real-world flight conditions. The ALSIM AL250 has also been successfully utilized in previous aviation research, establishing its validity as a simulation tool and demonstrating its effectiveness in studying various aspects of flight training and performance [290–293]. The simulator lab provided a consistent and distraction-free study conditions. Environmental controls regulated temperature, humidity, and ambient noise, minimizing external influences on participant performance. Adjustable overhead lighting was set to a neutral brightness level to provide consistent ambient lighting, ensuring optimal visibility without glare or reflections on the simulator's flight deck.

Lighting settings were standardized across all sessions, while the lab's fully enclosed design eliminated external light sources, preventing variability from natural daylight or other environmental factors.



Figure 14. ALSIM AL250 flight simulator at the WISA simulator lab (interior view)

5.3.1.2 AR device

The AR device used in this study was the second-generation HoloLens, a mixed reality head-mounted display (HMD) selected for its advanced capabilities and suitability for delivering dynamic and immersive AR-based training in a flight simulation environment [294]. Key features of the HoloLens 2 include high-resolution see-through holographic lenses with a resolution of 1440×936 pixels per eye and a diagonal field of view (FoV) of 52 degrees, providing sharp and vivid visualizations. Its precise spatial mapping and intuitive interaction features, such as advanced hand and eye tracking, allowed participants to naturally engage with virtual content, ensuring seamless integration into the simulator environment. The device's voice command support and gesture-based controls further enhanced usability by enabling hands-free operation, an important factor for efficient training scenarios. The HoloLens 2 is equipped with an array of built-in sensors, including an Inertial Measurement Unit (IMU), four visible light cameras for head tracking, two infrared cameras for eye tracking, a 1-megapixel Time-of-Flight (ToF) depth sensor, and an ambient light sensor. These sensors ensured accurate alignment of virtual elements with the simulator cockpit, creating a cohesive and immersive training experience. Additionally, spatial sound speakers integrated within the frame provided directional audio feedback, further enhancing the sense of immersion. The ergonomic, weight-balanced design with adjustable straps ensured a secure and comfortable fit, accommodating participants with glasses without compromising stability. A flip-up visor allowed seamless

transitions between AR and the physical environment, streamlining interactions without the need to remove the device, thereby enhancing overall usability and training efficiency.

5.3.1.3 Application on AR device

The AR application used in this study was developed for the Microsoft HoloLens 2 to provide real-time AR cues (augmented instructional overlays) during the simulation of predefined flight procedures in the ALSIM AL250 flight simulator. Built using the Unity 3D engine and tailored specifically for the ALSIM AL250, the application projected interactive augmented instructions directly into the participant's field of view. These instructions delivered step-by-step guidance, highlighting relevant instruments and controls on the flight deck to facilitate the accurate and sequential execution of flight procedures with dynamic, hands-free support. The application was developed using Unity's AR Foundation package and the MixedRealityToolkit (MRTK) to enable spatial mapping, allowing precise alignment of AR cues with the physical instruments and controls in the cockpit. Interactions with the AR system were facilitated by the HoloLens 2's gesture recognition functionality, offering two modes of engagement. Distant AR overlays were operated using hand rays and the air tap gesture, with participants directing their gaze to position the cursor and performing hand gestures to interact. For closer AR overlays, participants could engage with them through fingertip touch, allowing direct interaction. This combination of hand ray and touch interaction created an intuitive and immersive interface for executing flight procedures. Thorough calibration ensured accurate spatial mapping and alignment of AR cues within the simulator cockpit, guaranteeing that virtual elements appeared exactly as intended. This process confirmed seamless integration with the simulator environment, enhancing procedural accuracy.

5.3.2 Study Design

The study employed a within-subject design to compare the effectiveness of two assistive training modalities: a traditional paper-based method (M1) and an AR-integrated HMD application (M2). The paper-based modality required participants to follow written step-by-step instructions to complete flight procedures, serving as the baseline condition and reflecting current civil aviation practices. In contrast, the AR-integrated HMD modality provided real-time augmented reality cues projected into the participants' field of view, offering interactive, hands-free guidance. These cues visually highlighted relevant instruments and controls, facilitating accurate and sequential execution of flight procedures. This design allowed for direct comparison between static, text-based instruction and dynamic, immersive AR-based assistance, evaluating their respective impacts on procedural accuracy and overall training effectiveness.

To evaluate performance across both modalities, two distinct flight procedures were established in collaboration with a Certified Flight Instructor (CFI): a 'run-up and before-takeoff' checklist (P1) and a

landing from the final leg position (P2). These procedures were adapted from standard flight operations for their relevance, practicality, and manageable complexity. It was ensured that the two procedures differed significantly in nature—P1 involved executing a structured checklist, while P2 required dynamic, real-time control during flight. This contrast allowed for a comprehensive assessment of the training modalities across both static and operational flight procedures, reflecting the diverse cognitive and motor skills essential for routine flight operations. Detailed procedural steps are outlined in Table 8.

For procedural consistency, the simulator environment was configured to mirror real-world conditions at the Region of Waterloo International Airport (YKF) under CAVOK (Ceiling and Visibility OK) settings for both P1 and P2. This ensured zero wind, no turbulence, and unobstructed visibility. For P2, the aircraft was positioned at a predetermined final leg approach point, representing the aircraft's approach phase prior to touchdown. The aircraft was positioned at 1812 feet ASL with an airspeed of 70 knots, aligned with YKF at latitude 43.48° N and longitude -80.32° W. The aircraft's true heading was set to 245° with a magnetic heading of 255°, aligning it with the runway approach path. The initial position placed the aircraft 4 nautical miles from the runway threshold, providing sufficient distance for descent, flare, and touchdown. This configuration allowed participants to manage airspeed, glide path, and alignment during the final approach under controlled conditions.

Table 10. Detailed steps for flight procedures

<i>Run-up & Before Take-off Checklist</i>	<i>Landing from Final Leg Position</i>
1) Set the parking brake 2) Ensure flight controls are free & correct. Exercise yoke rotation in left & right direction ▪ With each rotation, look over to the aileron of each wing (near the wingtip), and make sure they are responding to rotation in the right direction. ▪ Left direction will allow the left aileron to rise and the right aileron to come down. ▪ Right direction will allow the right aileron to rise and left aileron to come down. 3) Check and set flight instruments. ▪ Airspeed indicator (ASI): At zero. ▪ Attitude indicator (AI): Flushed with the horizon. ▪ Altimeter: Set pressure (29.92inHg), confirm indication is within +/- 50 ft field elevation (using standard pressure for simulator). ▪ Turn Coordinator (TC): No flag, wings level, ball centered. ▪ Heading indicator (HI): Confirm with magnetic compass. ▪ Vertical-speed indicator (VSI): At zero. 4) Check for sufficient fuel quantity. 5) Set mixture (rich) 6) Set fuel selector value for Left Engine to Left Tank. 7) Set elevator trim (takeoff) ▪ Move the trim control wheel and notice the dial deflection across elevator trim indicator.	1) Maintain runway centerline using a combination of flight controls, power & rudder pedals application. Check flight instruments indications. ▪ Manipulate the yoke and rudder pedals together to maintain the track of the airplane along the runway centerline. ▪ Flight instrument settings: - Airspeed indicator (ASI): 65-70kts (flaps up). - Altimeter: Altitude decreasing. - Turn Coordinator (TC): Wings level, ball centered (remain coordinated). - Heading indicator (HI): Confirm heading matches runway heading. - Vertical-speed indicator (VSI): No more than 1000 fpm descent. 2) Reduce power to 1500 RPM or less. Below airspeed 110 kts, bring flaps down to first notch (TO/APPR position). Verify approach speed is ~70kts with first notch of flaps. ▪ With flaps in TO/APPR position, airspeed should be around 70kts. ▪ Adjust power setting & yoke pitch as needed to maintain the 3-degree glide slope (descent). - Use power to adjust the descent rate. - Use pitch to adjust your airspeed. 3) Check air speed is in white arc. Bring full flaps down (if needed). Approach at 65 kts with full flaps.

- Adjust the trim wheel just the right amount to level trim dial to the neutral or takeoff position (straight and level flight). 8) Set throttle (1800RPM) - Gently ease throttle lever into forward position. - Adjust throttle until tachometer dial shows 1800 RPM. 9) Check magnetos (only Left Engine) - Turn left mag Off. Notice the RPM drop on tachometer. Switch left mag back to On, and notice RPM revive back to 1800 RPM. 10) Check vacuum gauge: look over VAC indicator, and ensure needle is in the green zone. 11) Check ammeter & engine instruments (oil temp, oil pressure, fuel flow & flaps) - Ammeter: Verify if ammeter is reading a charge (needle deflected upwards). - Ensure oil Temp, oil Pressure & Fuel Flow Indicator are in the green zone. - Flaps: Ensure they are set in take-off position (up position). 12) Check carb. heat (Only Left Engine) - Pull the carburetor heat knob to ON position. - Notice the drop in RPM on the tachometer (RPM indicator). Push the carburetor heat knob to OFF position, and notice RPM revive back to 1800 RPM. 13) Check annunciator panel - Scan the annunciator panel and ensure none of the annunciator lights are illuminated. - Press the test button to ensure all the annunciator lights are working. Release button after. 14) Set throttle (1000RPM) - Gently ease throttle lever into backward position. - Adjust throttle until tachometer dial shows 1000 RPM. 15) Set strobe lights	- Adjust power setting & yoke pitch as needed to maintain the 3-degree glide slope (descent). - Use power to adjust the descent rate. - Use pitch to adjust your airspeed. 4) Coordinate descend using a combination of flight controls and power. When above the aim point, begin to reduce power and level off to flare. - Maintain coordination with flight controls and adjust power to ensure descend isn't too drastic. 5) Upon landing, ensure powder is idle. Push on both rudder pedals while maintaining centerline on the runway and apply brakes. Execute manual brake application while pressure is being applied onto rudder pedals. 6) Complete after landing checklist after you have left the runway. - Flaps - UP - Carb heat - OFF - Landing light – OFF - Strobes – OFF
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5.3.3 Participants

A power analysis was conducted using GPower 3.1.9.6 software [295] to determine the minimum number of participants required for the study. The analysis, set to the t tests family for the statistical test "Means: Difference between two dependent means (matched pairs)" was performed with an effect size of 0.65 (Cohen's d) and an alpha level of 0.05. The results indicated that a minimum of twenty-eight participants would be required. The medium effect size of 0.65 was selected based on findings from similar studies on AR usability in education and training contexts, including multiple meta-analyses of empirical studies examining AR's effects on knowledge acquisition and skill performance [33,272,273,276,277,296–299]. To provide additional statistical power and account for potential variability, the final sample size was increased to thirty participants, exceeding the minimum requirement determined by the power analysis.

Thirty student pilots (10 females, 20 males) were recruited from the University of Waterloo's aviation program, where the study was advertised. Recruitment targeted novice pilots with less than 10 hours of flight experience. Participants had an average age of 19.3 years (SD = 0.75) and an average of 6.9 flight

hours (SD = 7.61). All participants had normal or corrected vision, normal hearing, and no prior diagnosis of neuropsychiatric or neurological disorders or learning disabilities. They were physically and mentally fit to operate a flight simulator. None of the participants had prior experience with AR technology, ensuring their exposure to AR during the study was both unbiased and consistent. Additionally, participants were unfamiliar with the specific flight simulator used in this study. Participants were compensated with a predetermined cash payment for their voluntary participation.

Participation lasted up to 90 minutes, divided into two main phases. The first 30 minutes focused on familiarization and preparation. Participants began by reviewing an information letter outlining the study's purpose, their rights and responsibilities, and the expected data collection processes. They were encouraged to ask questions, reminded of their right to withdraw at any time. After all questions were addressed, participants gave their informed consent to proceed. Data confidentiality was ensured through anonymized records. After providing consent, participants completed a familiarization session designed to ensure comfort and confidence with the study setup. The session began with hands-on experience using both assistive modalities. Participants were first introduced to the AR application through the HMD, where they were shown how the AR application integrates augmented information into their operating space and were trained to interact with AR cues using hand gestures. Practice sessions with the AR-integrated HMD allowed them to test gestures and build familiarity with the AR setup. Following this, participants experienced the paper-based modality, practicing how to follow written step-by-step instructions. This dual exposure ensured participants were equally familiar with both modalities before proceeding to the simulation phase. Subsequently, they were seated in the simulator, but no explanations or demonstrations of the cockpit controls and instruments were provided. The remaining 60 minutes were dedicated to the simulations, during which participants performed the predefined flight procedures both with and without the training modalities.

The study was approved by the University of Waterloo's Research Ethics Board (#46272) and conducted in strict adherence to the board's ethical guidelines and regulations.

5.3.4 Study Procedure

The study procedure followed a structured sequence to ensure consistency and thorough data collection across all participants. Figure 15 provides a high-level overview of the procedure, with the detailed steps outlined as follows: 1) Study Briefing and Consent: Participants received a comprehensive briefing that outlined the study's purpose, objectives, training modalities (M1 and M2), and participation expectations. The briefing also addressed measures for data confidentiality and participant safety. After reviewing the information letter and asking any questions, participants provided informed consent to proceed. 2) Pre-Study Data Collection: Participants completed a pre-study questionnaire to gather demographic information

and professional details, including age, gender, education level, and flight experience. 3) Familiarization and Calibration: Participants took part in a hands-on familiarization session for both assistive training modalities (M1 and M2) and the simulator environment. Following this, participants were seated in the flight simulator for AR device calibration. 4) Flight Procedure Briefing and Training Simulation Assignment: Participants received a briefing on the two flight procedures, P1 and P2. To counterbalance the order of flight procedures and training modalities, a Latin square design was applied, ensuring that each participant experienced a unique sequence of the two procedures (P1 and P2) and the two training modalities (M1 and M2). The Latin square was configured to cover all possible sequences of flight procedures and modalities, such as P1 with M1 followed by P2 with M2, P1 with M2 followed by P2 with M1, P2 with M1 followed by P1 with M2, and P2 with M2 followed by P1 with M1. Each participant was assigned to one of these sequences in a rotating order to evenly distribute the experiences. This counterbalancing approach minimized the influence of practice, or learning effects, ensuring that results reflected the true impact of the training modalities rather than the order in which they were experienced. Additionally, a modulating task was introduced between the two procedures to reset cognitive load and mitigate carryover effects from the first simulation. During the execution of flight procedures, a CFI accompanied participants in the simulator and assisted them as needed to support the successful completion of assigned flight procedures using the respective training modalities. The CFI also documented the assistance provided. To ensure consistency and alignment with the study objectives, the CFI underwent the same briefing and consent process as the participants, allowing the CFI to effectively guide participants while maintaining the integrity of the study framework. Figure 16 illustrates a participant engaging in two separate training simulations, showcasing the execution of two distinct flight procedures using different training modalities: P1 performed with M2, and P2 conducted with M1. Also, Figure 17 highlights examples of AR cues presented during the training simulation of P1 using M2. These cues guided the participant through steps such as setting the parking brake, adjusting the mixture, checking fuel quantity, and activating the strobe lights by highlighting specific cockpit controls or instruments with attention guidance objects (circles or rectangles) and providing textual instructions. 5) Post-Simulation Feedback: After completing the training simulations, participants completed post-study questionnaires to evaluate their experiences with each training modality. Subsequently, semi-structured interviews were conducted to gain deeper insights into their experiences, perceptions, and challenges associated with the training modalities during the training simulations. The interview questions are presented in Table 9. 6) Skill Retention Assessment: In the final phase of the study, participants repeated both flight procedures (P1 and P2) without the support of either training modality to assess skill retention. The retention assessment simulations were conducted after the training simulations, following a brief 5-minute break to mitigate fatigue. A CFI observed and evaluated their performance to assess skill retention.

Each training simulation, whether involving P1 or P2 and M1 or M2, lasted up to 15 minutes across all participants. During the final phase, retention assessment simulations lasted between 10 and 15 minutes.

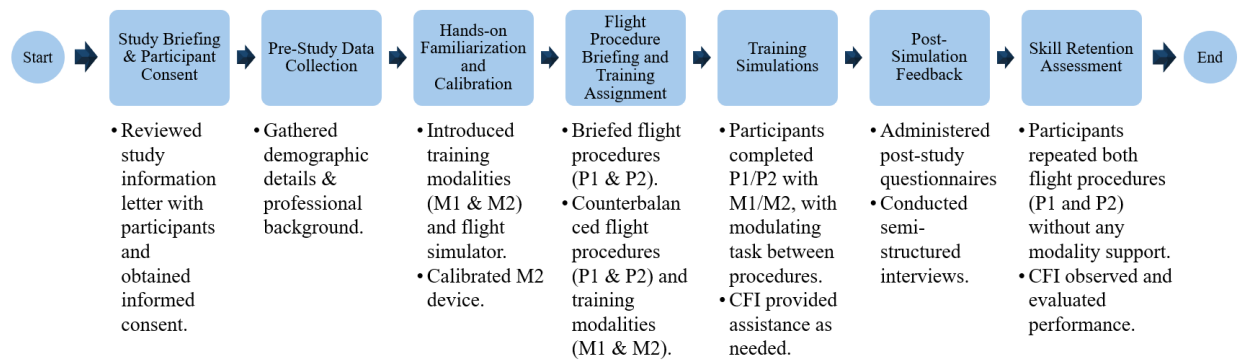


Figure 15. Study procedure workflow



Figure 16. A participant performing two flight procedures under different training modalities: P1 using M2 (left) and P2 using M1 (right)

Table 11. Semi-structured interview questions

1. How would you describe your overall experience using AR compared to the paper-based training modality? <i>Follow-up: Which aspects of the AR training stood out positively or negatively?</i>
2. In what ways do you think AR training modality could contribute to improving student pilots' flight competency and proficiency compared to paper-based modality? <i>Follow-up: Are there particular flight procedures or training exercises where you think the AR training could offer a significant advantage over paper-based training?</i>
3. Did you encounter or do you foresee any usability challenges with AR training modality? <i>Follow-up: If yes, what suggestions do you have for improving the AR training to make it more effective or user-friendly? If no, are there any enhancements you would still recommend to further refine AR training?</i>
4. If you had the option to use only one modality for future training, which would it be? <i>Follow-up: Why - What factors contributed to this perception?</i>



Figure 17. Examples of AR cues presented during the training simulation of P1 using M2, guiding the participant through steps such as setting the parking brake (top left), adjusting the mixture (top right), checking fuel quantity (bottom left), and activating the strobe lights (bottom right)

5.3.5 Method of Evaluation

Participant experiences and performance across the two training modalities (M1 and M2) were assessed using seven dependent variables (DVs): mental workload, situation awareness, user acceptance, sickness, instructor assistance during training, memory retention errors, and overall retention assessment outcomes. These variables were selected for their ability to provide a multidimensional perspective on training effectiveness [292,300–303]. Four DVs—mental workload, situation awareness, user acceptance, and sickness—were assessed immediately after the training simulations using validated post-study questionnaires. Instructor assistance was recorded during the training simulations to measure participants' reliance on instructor support. Memory retention errors and retention assessment outcomes were evaluated as part of the retention assessment simulations, where participants performed the two flight procedures (P1 and P2) independently, without any support from the training modalities.

Mental workload, measuring the cognitive demands of each modality, was evaluated using the NASA Task Load Index (NASA-TLX) questionnaire, which assesses six dimensions: performance, effort, frustration, mental demand, temporal demand, and physical demand [304–306]. Participants rated each dimension on a 1–100 scale, with raw scores averaged to produce a composite workload score between 0 and 100. Higher scores indicated greater cognitive demands. Situation awareness, capturing participants' ability to perceive, understand, and respond to provided information, was assessed using the Situation Awareness Rating Technique (SART-10D) [301,307–310]. This 10-item questionnaire measures attentional demand, supply, and situational understanding. Each item was rated on a scale from 0 (low) to 7 (high), producing a composite situation awareness score ranging from -7 to 14 using the formula: Understanding – (Demand – Supply). Higher scores reflected better situational awareness, while lower scores indicated resource limitations. User acceptance, evaluating the usability and adoption potential of each modality, was measured using the Technology Acceptance Model (TAM) [311–313]. The TAM includes 12 statements across two subscales: perceived usefulness (PU) and perceived ease of use (PEOU). Each subscale was rated on a 7-point Likert scale, with subscale averages combined into an overall TAM score ranging from 1 to 7. Higher scores indicated stronger perceptions of usefulness and ease of use. Sickness, reflecting physical discomfort associated with the modalities, was assessed using the Simulator Sickness Questionnaire (SSQ) [292,314–316]. This 16-item tool evaluates symptoms across three categories: nausea, oculomotor discomfort, and disorientation. Ratings for each symptom, collected on a 4-point Likert scale (0–3), were weighted using specific factors: nausea-related measures were multiplied by 9.54, oculomotor-related measures by 7.58, and disorientation-related measures by 13.92. The weighted subscales were summed, and the Total Score (TS) was calculated by multiplying this sum by 3.74. Higher TS values, up to a maximum of 300, indicated greater sickness severity. Originally developed for flight simulators, the SSQ is now widely used in both immersive and non-immersive environments. In this study, the SSQ was consistently administered across both modalities to enable direct comparison.

Instructor assistance levels reflected participants' ability to complete flight procedures independently, while memory retention errors and overall retention assessment outcomes provided insights into their procedural understanding and retention of skills [300]. These measures were recorded and evaluated by the CFI to ensure consistency and accuracy in assessing participant performance. The instructor assistance during training simulations was recorded by categorizing the level of support participants needed to complete the flight procedure. This was classified as either zero assists, indicating independent completion without intervention, or any number of assists, where guidance was provided without explicitly instructing the participant on how to perform specific steps of the flight procedure. Memory retention errors were documented as deviations from expected operational intentions or procedures during retention assessment simulations, with the total count recorded regardless of error type to assess lapses in knowledge and

accuracy during flight procedure execution. Overall retention assessment outcomes were classified into three categories: Complete Success, reflecting accurate procedure completion without errors; Partial Success, indicating completion with errors; and Failure, signifying the inability to complete the procedure. To mitigate potential observer bias, a single CFI conducted all assessments, adhering to the standardized criteria outlined in the Transport Canada Flight Test Guide for PPL [317]. This ensured consistent and objective evaluations across all participants. Additionally, the CFI was blinded to the specific training modality used by participants for each flight procedure during the training simulations, preventing prior modality exposure from influencing the evaluations conducted during the retention phase.

5.3.6 Data Analysis

The analysis examined the impact of the two training modalities (M1 and M2) across all dependent variables (DVs) using a combination of descriptive and inferential statistics. Normality for each DV was assessed using the Shapiro-Wilk test. For DVs that met normality assumptions, paired samples t-tests were conducted to analyze differences in results across the modalities. When normality assumptions were violated, non-parametric Wilcoxon signed-rank tests were performed as a post hoc analysis. Statistical significance was set at $\alpha=0.05$, and effect sizes of paired data were calculated to support result interpretation. Cohen's d was used to measure effect size for normally distributed data, whereas Cliff's Delta was applied to assess effect size in non-normally distributed data [318]. For variables where paired t-tests or Wilcoxon signed-rank tests did not reveal statistically significant differences, Bayesian paired samples t-tests were employed to provide additional validation. The DV 'overall retention assessment outcomes', being categorical, was analyzed using chi-square test, as parametric tests were not applicable. Furthermore, thematic analysis was employed to analyze insights gathered from the semi-structured interviews.

5.4 Results

The analysis across NASA-TLX, SART, TAM, SSQ, instructor assistance during training, memory retention errors, and overall retention assessment outcomes provided valuable insights into the differences between AR and Paper conditions, highlighting both their strengths and limitations.

For NASA-TLX, the AR condition demonstrated a significantly lower perceived workload compared to the Paper condition. The mean NASA-TLX score for AR was 36.72 (SD = 10.48), substantially lower than Paper's mean score of 64.11 (SD = 13.66). The Shapiro-Wilk test confirmed normality of paired differences ($W = 0.98$, $p = 0.74$), validating the use of parametric tests. A paired t-test identified a statistically significant difference, $t(29) = -8.66$, $p < 0.001$, with a large effect size (Cohen's $d = 1.58$) for the paired data, indicating a meaningful reduction in workload for the AR condition. The SART analysis revealed

significantly enhanced situational awareness in the AR condition. The mean SART score for AR was 6.63 (SD = 1.05), markedly higher than Paper's mean of 3.40 (SD = 1.06). Normality of paired differences was confirmed using Shapiro-Wilk test ($W = 0.97$, $p = 0.49$), and a paired t-test showed a highly significant difference, $t(29) = 11.33$, $p < 0.001$. The large effect size for paired data (Cohen's $d = 2.07$) emphasized the practical significance of AR in improving situational awareness. Similarly, the TAM analysis demonstrated greater user acceptance for AR. The mean TAM score for AR was 5.93 (SD = 0.75), significantly higher than Paper's mean of 3.45 (SD = 0.98). The Shapiro-Wilk test validated normality ($W = 0.97$, $p = 0.49$), and a paired t-test revealed a statistically significant difference, $t(29) = 9.64$, $p < 0.001$. The large effect size for paired data (Cohen's $d = 1.76$) underscored the substantial advantage of AR, reflecting greater perceived usefulness and ease of use. In contrast, the SSQ analysis found no significant difference in sickness symptoms between the AR and Paper conditions. The mean SSQ score for AR was 101.25 (SD = 87.42), slightly higher than Paper's mean of 91.60 (SD = 112.70). The Shapiro-Wilk test confirmed normality ($W = 0.97$, $p = 0.53$), but the paired t-test indicated no statistically significant difference, $t(29) = 0.47$, $p = 0.64$. A Bayesian paired samples t-test ($BF_{10} = 0.22$) further supported these findings, indicating no substantial difference between conditions. The Bayesian effect size (median = 0.08, 95% credible interval: [-0.26, 0.42]) and Cohen's d (0.09) for paired data suggested a negligible practical effect, reinforcing the conclusion that sickness symptoms are comparable between AR and Paper, with no meaningful advantage for either condition. These results, also summarized in Figure 18, demonstrate significant advantages of AR over Paper in reducing workload, enhancing situational awareness, and improving user acceptance, while confirming no meaningful difference in sickness symptoms between the two conditions.

During training simulations, participants using AR required significantly less instructor assistance ($M = 1.07$, $SD = 1.20$) compared to those using Paper ($M = 3.23$, $SD = 2.16$). The Shapiro-Wilk test ($W = 0.918$, $p = 0.02$) indicated that the paired differences were not normally distributed, necessitating the use of a non-parametric Wilcoxon signed-rank test. The test revealed a statistically significant reduction in instructor assistance required for AR compared to Paper ($W = 5$, $p < 0.001$). The large effect size (Cliff's Delta = 0.6) for paired data underscores the practical advantage of AR in fostering participant independence and reducing reliance on instructor support. These results are summarized in Figure 19. Similarly, during retention assessment simulations, participants who received AR training made slightly more errors ($M = 2.77$, $SD = 1.48$) than those with Paper ($M = 2.20$, $SD = 2.07$). The Shapiro-Wilk test ($W = 0.73$, $p < 0.001$) indicated non-normal distribution of paired differences, prompting the use of a Wilcoxon signed-rank test. The test identified a statistically significant difference in memory retention errors between AR and Paper ($W = 103.5$, $p = 0.03$). The effect size (Cliff's Delta = 0.31) for paired data suggests a small to moderate practical difference, indicating that while AR participants made slightly more errors than those using Paper,

the magnitude of this difference is meaningful but not large. This implies that the additional errors associated with AR modality are statistically significant but not practically substantial. These findings are summarized in Figure 20. For overall retention assessment outcomes, a Pearson Chi-Square Test for Independence was conducted to examine the relationship between the training modality (AR or Paper) and outcome categories (Complete Success, Failure, Partial Success). Figure 21 illustrates the observed frequencies of overall retention assessment outcomes among all participants. Due to the categorical nature of the data, parametric tests were not applicable, making the Chi-Square test an appropriate choice. The test yielded a Chi-Square value of $\chi^2(2) = 3.16$, $p=0.21$, indicating no statistically significant association between training modality and overall retention assessment outcomes. This suggests that differences in "Complete Success," "Failure," and "Partial Success" between AR and Paper modalities are likely due to random variation rather than a true effect of the training modality.

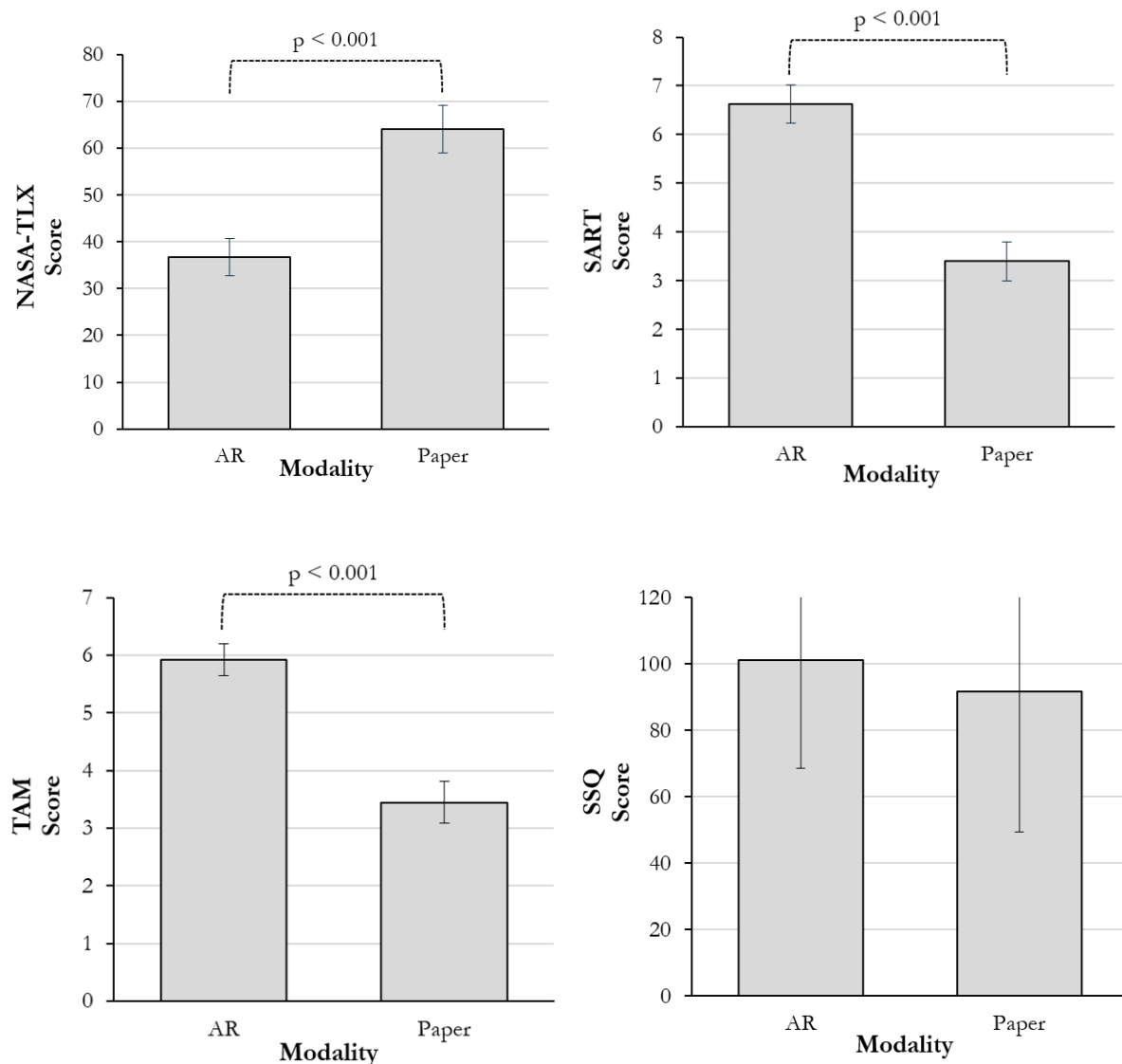


Figure 18. Comparison of training modalities (AR vs. paper) for NASA-TLX (top left), SART (top right), TAM (bottom left), and SSQ (bottom right). Error bars show 95% CI.

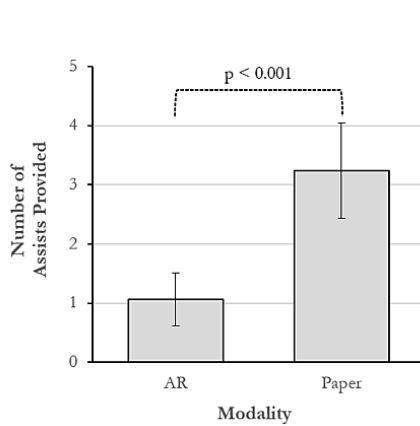


Figure 19. Comparison of training modalities (AR vs. paper) for number of assists provided (Error bars show 95% CI.).

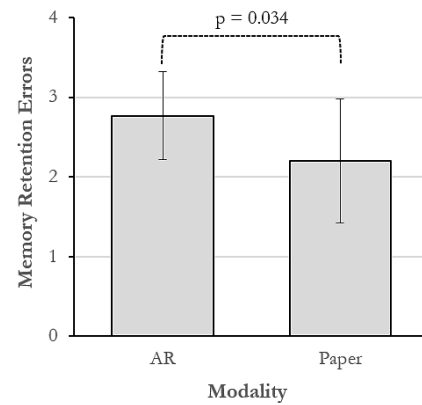


Figure 20. Comparison of training modalities (AR vs. paper) for memory retention errors (Error bars show 95% CI.).

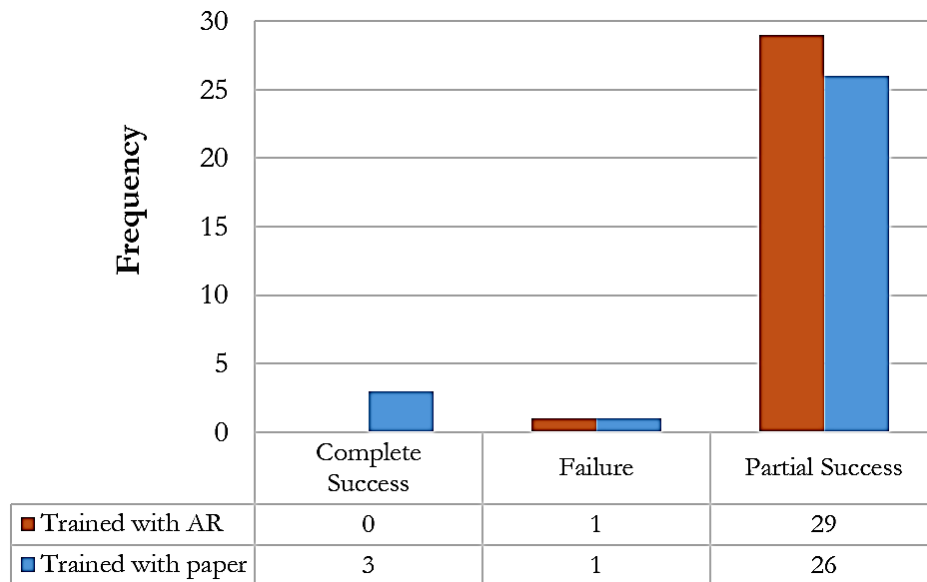


Figure 21. Observed frequencies of overall retention assessment outcomes among all participants

The semi-structured interview responses, designed to explore participants' experiences, perceptions, and challenges with training modalities during simulations, were analyzed using thematic analysis following

Braun et al.'s methodology [319]. To ensure reliability, two researchers independently analyzed the responses, applying both deductive and inductive coding methods. Deductive coding followed a theoretical approach, organizing data into predefined categories based on existing literature: AR Integration [21–23,280,283,286–288], which explores AR's potential applications in pilot training; Procedural Training [276,278,293,296,303], which focuses on structured, step-by-step guidance to enhance accuracy, consistency, and real-world readiness; and Training Effectiveness [33,272,273,277,289,300], which assesses knowledge retention, skill development, and AR's potential to facilitate self-paced, interactive learning while reducing instructor dependency. In contrast, inductive coding followed a data-driven approach, allowing themes to emerge organically from participant responses, enabling the identification of unexpected insights. These emergent themes included Integrative and Cost-Efficient Training, which highlighted AR's role in reinforcing both foundational and advanced procedures while addressing cost-efficiency concerns; Cognitive Load Management, which explored AR's ability to reduce mental strain by integrating instructional guidance seamlessly into the learning workflow; Progression and Independence, which emphasized the transition from guided assistance to autonomous procedural execution, fostering confidence and retention; and Hardware and Usability Limitations, which identified challenges related to HMD ergonomics, interface usability, and constraints associated with prolonged use. This analysis revealed interrelated concepts, leading to the development of four interconnected themes: 'Innovative and Dynamic Learning with AR', which highlights AR's potential to supplement traditional instruction through structured, interactive, and visually guided training, particularly in simulators and controlled environments; 'AR for Early-Stage Flight Training Enhancement', which emphasizes AR's role in supporting novice pilots by aiding pre-flight preparation and reinforcing procedural accuracy in structured settings; 'Improving AR Usability for Intuitive and Adaptive Learning', which underscores the need to refine AR-based training by improving hardware ergonomics, instructional design, cognitive load management, and system responsiveness to enhance efficiency and immersion; and 'AR's In-Flight Usability and Training Limitations', which addresses concerns regarding AR's practicality in real-flight conditions, highlighting visibility issues, cognitive load, and system reliability challenges. The findings corresponding to each theme are presented below, based solely on participant feedback, without interpretation or influence from the authors.

Innovative and Dynamic Learning with AR

Participants shared that AR-based training offers a significant advantage over traditional paper instructions by integrating step-by-step guidance with visual overlays, making training more intuitive and efficient. Many found that real-time visualization helped them quickly identify procedural steps, such as highlighting the flap lever with an instruction to set the correct position, reducing uncertainty and improving cockpit

familiarity. “Being able to see where instruments and controls are makes a huge difference. It just clicks way faster than trying to figure it out from instructions on a piece of paper” one participant noted. A common challenge participants identified with paper-based instructions, often structured as checklists, is their assumption of prior knowledge, which can lead to confusion when generic directives such as ‘Set flight instrument’ lack clear step-by-step guidance. They explained that AR could eliminate this ambiguity by providing clear visual overlays that remove guesswork, making instructions easier to follow. One participant described this as “AR pushes you from step one to step two, which is very helpful”, emphasizing how structured AR guidance maintains procedural flow and reduces the risk of missing steps. Another added, “The biggest advantage it has over paper instructions is that it actually shows you where everything is”.

Participants also highlighted AR’s ability to reduce distractions and cognitive load by keeping their focus on the task at hand, eliminating the need to constantly shift attention away from the cockpit—a common issue with paper-based instructions that require manually locating items and referencing materials separately. “Projecting it is a little more efficient because there’s no kind of looking down and up” one participant noted. They emphasized that AR’s structured approach reinforces each step visually, keeping them on track and reducing the likelihood of errors. One participant explained, “It’s going to help avoid any missteps, for sure”. Beyond improving clarity and reducing mistakes, participants valued AR’s interactive and dynamic guidance system, which adapts to user actions and displays instructions based on what they need to focus on at any given moment. “Visuals indicating where to go or where to look for that instruction, very helpful for beginners”, one participant shared. Another added, “It’s kind of hands-on; you get the hang of doing it with motions rather than just reading it on paper”.

Participants acknowledged that while there is an initial learning curve with AR-based learning, the system becomes intuitive with practice as users become familiar with it. One participant noted, “Getting used to the new technology could take some time, but apart from that, this can be a great tool”. Others shared that as they became more comfortable with AR, training simulation felt smoother and more efficient. “Once you get the hang of it, navigating the AR system feels more natural and intuitive”, one participant explained. Many suggested that structured onboarding or additional training could further ease the transition and improve usability.

Participants described the limitations of traditional dual instruction flight training, explaining that verbal communication alone can be difficult to process and retain, especially in the chaotic cockpit environment, where high cognitive load and stress make it challenging to focus. Many shared that keeping up with an instructor’s verbal commands while simultaneously scanning and interpreting key cockpit instruments—such as checking airspeed, monitoring altitude, or assessing engine performance—requires rapid cognitive

shifts, which can be overwhelming. They shared that as novice pilots, they often hesitate to ask questions or express uncertainties during verbal assessments due to a fear of failure or being judged, which they felt further hindered their learning process. Given these challenges, participants saw AR as a valuable tool for reinforcing flight concepts and procedures through interactive, visual instruction. They explained that AR can bridge the gap between theory and practice, allowing students to see dynamic visualizations of complex topics in both simulator and classroom settings. Many believed that AR enhances accessibility by catering to different learning styles, particularly for visual learners who may struggle with traditional instructor-led verbal instruction. One participant noted, “This will help visual learners because a lot of the time in the plane, it’s just listening to instructors saying stuff”. Others pointed out that verbal-only instruction often leads to forgetfulness, whereas AR’s combination of visual and written reinforcements could help improve retention. As one participant shared, “It’s easy to forget things but for someone who learns visually and benefits from having instructions written down, this would probably make a big difference”.

Beyond AR’s instructional benefits, participants described AR as an engaging and interactive tool that made training more immersive and enjoyable, particularly since none had prior experience with the technology. Many see real-time visual prompts and alerts as effective tools for reinforcing instructor guidance, which can help maintain focus on critical instruments and controls while strengthening mental models for improved comprehension and decision-making. One participant remarked, “AR lessons in a simulator can provide a more engaging, practical, and confidence-boosting learning environment.” They emphasized that AR’s structured and interactive approach deepens engagement, ensuring training is not solely reliant on auditory instruction, making it more adaptable and inclusive—especially for novice pilots.

AR for Early-Stage Flight Training Enhancement

Participants widely agreed that AR holds significant value as a training aid in early-stage flight training for novice pilots. However, they emphasized that it should complement—not replace—traditional instruction with CFIs, as hands-on real-flight experience remains indispensable for developing real-world flying skills. Many felt AR would be most beneficial during the first 15–20 flight hours, when novice pilots are still developing fundamental skills such as basic maneuvers, navigation, emergency procedures, and radio communications. Building on this, they highlighted that AR would be most effective in structured environments such as simulators or ground training sessions, where novice pilots could both enhance pre-flight preparation and reinforce learning throughout early flight training.

Participants saw AR as a tool to enhance pre-flight preparation, helping novice pilots refine basic skills before stepping into an aircraft. They suggested that by familiarizing with procedures in a structured manner, student pilots could make in-flight training more efficient, reducing training costs and maximizing learning outcomes. One participant noted, “It would be really useful to get comfortable with all the basic

lessons first and then move on to more advanced stuff”. Takeoffs and landings were identified as particularly challenging since they require simultaneous coordination of multiple factors. Participants felt that AR could support early cockpit familiarization and reinforce key procedural flows in a low-pressure environment, allowing them to build muscle memory before transitioning to dual instruction training exercises. One participant explained, “When you're learning to fly, takeoff and landing are the biggest hurdles. There's so much happening at once, and you don't have much room for error. Being able to run through the steps using AR first would make it way easier to get comfortable before doing it for real”.

AR-assisted simulations were also seen as a valuable reinforcement tool for flight circuits—takeoff, pattern flight, and landing—after each dual instruction lesson. They noted that in an actual flight, environmental factors like wind conditions, air traffic etc. can add complexity, making it difficult to focus solely on refining technique. Participants explained that dual instruction training builds progressively, meaning if they struggled to retain procedures from previous exercises, valuable flight time was often spent on review rather than progressing to new skills. Many felt that AR could bridge this gap, allowing them to rehearse procedures between lessons, ensuring procedural accuracy and making each flight session more productive. One participant noted, “If you don't fully remember what you did last time, you end up spending time in the aircraft relearning instead of moving forward. AR would let you go through those steps again in the sim, making sure you've got it locked in before your next lesson”. Emergency procedures training was another area where participants saw strong potential for AR. They felt that AR could provide structured, step-by-step guidance, making it easier to understand and reinforce complex recovery steps without the pressure of real-world consequences. Many emphasized that AR could teach them high-stakes scenarios—such as spins, spirals, or engine fire responses—as many times as necessary, helping them build confidence and develop instinctive decision-making skills before encountering these situations in an actual aircraft. One participant explained, “Instead of just memorizing a checklist, you'd see exactly what to do, where to look, what to check, what to adjust. And the best part is, you can run through different emergencies over and over until it really sticks”.

AR was also seen as particularly beneficial for aircraft familiarization, especially when transitioning to a new aircraft type during in-flight training. Since it is not practical for flight schools to assign a dedicated aircraft to each student pilot, they are instead assigned an aircraft from the available fleet for each lesson. As a result, student pilots could switch between different aircraft with variations in cockpit layouts, switch placements, and instrument configurations. Participants noted that this added complexity often makes it challenging to develop familiarity with a specific setup. They suggested that having AR guide student pilots through different cockpit layouts interactively before stepping into an aircraft could reduce this adjustment period, making training more intuitive and efficient. One participant shared, “When you're new to a plane,

you're spending a lot of time just figuring out where everything is. If AR could point things out and walk you through it, that would make it way easier to get comfortable faster”.

As novice pilots gain experience and transition to solo flying, participants envisioned that AR's role could naturally diminish, as real flight conditions could then become more critical for skill mastery. They explained that once foundational skills are ingrained, student pilots could prefer to rely more on instinct and real-time decision-making rather than structured AR guidance. One participant reflected, “The more you fly, the more the procedures just stick. At that point, I don't think using AR or even paper instructions would make much of a difference”. While some saw potential for AR in specific advanced training scenarios, such as practicing in adverse weather conditions, most agreed that upon transitioning to solo flying, hands-on flying experience should take precedence.

Improving AR Usability for Intuitive and Adaptive Learning

Participants noted that while the AR HMD's weight was comparable to standard pilot headgear, a lighter design would improve comfort, particularly for extended training sessions. “Most pilot headsets weigh about the same, but if the AR HMD were lighter, it would make a big difference in usability, especially during long sessions”, one participant explained. Many felt that a more compact design, such as AR-integrated smart glasses, would enhance wearability. “The HMD feels a bit bulky for training. If it could be as simple as a pair of glasses, that would be a game-changer”, another suggested. Beyond weight, participants highlighted challenges related to field of view (FOV) and tracking stability, particularly in the dynamic cockpit environment. While the HMD provided a reasonably large FOV, overlays positioned outside this area required frequent head movements to bring them into view. This underscored the need for a wider FOV to keep critical visual elements within the user's natural line of sight, reducing distractions and cognitive load. Additionally, participants noted that the HMD's tracking system struggled to keep up with rapid head movements, causing AR content to momentarily lag before stabilizing, which disrupted workflow and increased cognitive demand. One participant described encountering this issue during the before-takeoff checklist training simulation, “When I moved my head slowly, everything worked fine—the system highlighted the controls, and I could follow along easily. But if I turned too fast, like switching from the flap lever to carb heat, the visual overlays wouldn't show up instantly, which made me pause and wait for them to appear”. Others shared similar concerns, emphasizing that improving tracking accuracy would create a more seamless experience, especially in high-workload situations where quick instrument scans are essential. “If the tracking were faster, I wouldn't have to adjust how I move my head—it should just keep up”, one participant added. Some participants also mentioned difficulty shifting focus between visual overlays and physical cockpit instruments and controls, noting that this occasionally felt disorienting. They

stressed the importance of optimizing AR display placement to minimize cognitive strain, especially in fast-paced training environments.

Another major concern was AR setup time, which could eat into valuable simulator hours and increase training costs. “If setup takes too long, it’s burning into sim time and increasing costs”, one participant noted. Some suggested that a plug-and-play solution could make AR training more practical and efficient. Participants also pointed out that if AR equipment were expensive and integrated into training programs, it could significantly raise overall costs. Additionally, if students were required to purchase their own AR devices, affordability would be a key factor in adoption. “If the cost is too high, not many people are going to get on board with it”, one participant remarked.

Participants emphasized the importance of improving AR responsiveness, particularly in instruction delivery. Some noted that delays in system response times could slow down training sessions and reduce efficiency. “The way it picks up the instructions, I feel like it’s a bit slower. It could be made a lot faster”, one participant shared. Enhancing AR speed would not only improve routine training but also make the system more effective in high-pressure or emergency scenario training, where response times are critical.

To improve training efficiency, participants recommended streamlining instructional design by replacing text-heavy instructions with concise visual prompts, supplemented by optional auditory cues. “Instead of words, use prompts and don’t make it too text-heavy”, one participant noted. They also suggested hands-free interaction methods, such as voice commands or gaze-based controls, instead of manual clicking. “Clicking could be cumbersome; replace clicking with sound”, one participant explained. Another added, “Replacing hand gestures with voice commands or gaze movements would reduce distractions.”. Participants also proposed breaking down AR instructions into location-specific steps to prevent cognitive overload and improve procedural flow. Instead of grouping multiple actions into a single instruction, they suggested guiding users step-by-step through each task. “If it breaks things up a bit more—like instead of showing all ‘after landing steps’ as one instruction, it guides you through each step individually, first ‘Flaps up’, then ‘Carb heat off’, and so on—it would be much easier to follow”, one participant suggested. Additionally, they recommended an interactive feedback mechanism where actioned instruments or controls visually change color (e.g., from red to green) once completed, helping users track progress and build confidence.

Participants saw AR as a potential tool for enhancing situational awareness by providing subtle, real-time guidance, mimicking an instructor’s in-flight corrections. They suggested that AR overlays could detect and respond to changes in flight maneuvers, such as steep turns, stalls, and slow flight, by offering corrective cues. For example, steep turns were identified as a particularly challenging maneuver, requiring students to maintain a consistent 45° bank angle, stable altitude, and proper airspeed. Without real-time

feedback, students often underbank, overbank, lose altitude, or rely too heavily on trial and error. “If AR could display ideal bank angles and highlight deviations from the correct turn radius and show subtle cues or nudge corrections like ‘watch airspeed’ or ‘maintain bank angle,’ it would mimic instructor guidance, ensuring students stay on track”, one participant explained. These gentle reminders could help students internalize critical flight adjustments and develop instinctive decision-making skills over time.

Participants identified task fixation as a common challenge during flight training, where they often found themselves overly focused on a single element while neglecting other critical flight aspects. Some suggested that AR could help manage this by detecting fixation and providing timely reminders to redirect attention. Many shared examples of how this could be useful—during landing, some fixated on airspeed while losing track of the glide path or failing to monitor power settings. AR could step in with subtle cues like ‘Check glide slope’ or ‘Adjust power as needed’ to help them stay aware of all critical factors. Similarly, during steep turns, some admitted to focusing too much on bank control, causing them to overlook altitude or airspeed. In these cases, participants felt that AR could provide timely corrective cues, offering a gentle nudge to scan the altimeter and maintain proper pitch control, ensuring a more stable and precise maneuver.

To support learners at different skill levels, participants suggested customizable training modes that transition from detailed guidance to simplified cues, allowing students to progress from dependence to mastery. They envisioned a Beginner Mode with step-by-step guidance and visual pointers, an Intermediate Mode with checklist-style instructions without visual aids to encourage procedural recall, and an Advanced Mode designed for retention assessment, where the AR system removes prompts entirely and evaluates performance. “It could be like a few settings—beginner mode, where it actually shows you and points to it, then intermediate mode, where it doesn’t point, it just shows you the directions, and then a mode where there are no prompts at all, just evaluating if you’re doing things right”, one participant explained. To further enhance learning flexibility, participants proposed an on-demand assistance feature, such as a toggle or interactive button, that provides detailed explanations, imagery, or videos when needed. This would allow students to attempt steps independently while accessing support only when necessary, reinforcing procedural recall without unnecessary dependency. They felt that integrating such a feature alongside the progressive training modes would allow learners to gradually build confidence while ensuring guidance remains available for complex procedures or unfamiliar scenarios.

AR’s In-Flight Usability and Training Limitations

Participants shared that while AR can be effective for simulator training and classroom-based instruction, the AR setup experienced in the study is not yet mature enough for in-flight use. Many felt that practical limitations, such as visibility issues, potential distractions, and the discomfort of wearing the HMD, could

restrict its usefulness in real-world flight scenarios. One participant noted, “If you're flying with it, it could obstruct your vision.”

Participants described maintaining situational awareness in real-world flight conditions as already demanding, requiring them to actively scan for hazards while managing multiple factors. They explained that as student pilots, they must continuously monitor altitude, airspeed, and heading while remaining vigilant for traffic, weather changes, and terrain obstacles. Unlike a simulator environment focused solely on procedural execution, they emphasized that real-world flying requires continuous external awareness and rapid decision-making. Some worried that AR visual overlays could add cognitive load, potentially diverting attention from external scanning and reducing mental bandwidth for critical decisions. One participant expressed concern, stating, “It might take away some of the headspace”. This concern was particularly relevant for fundamental flight maneuvers such as turns, climbs, and descents, where situational awareness is just as critical as procedural execution. While participants acknowledged the benefits of procedural guidance, they stressed the importance of staying alert to other aircraft, obstacles, and terrain to ensure a safe flight path. Some noted that AR overlays could unintentionally draw focus inside the cockpit, causing pilots to fixate on procedural cues rather than maintaining an active lookout. As one participant put it, “It’s not just about getting the maneuver right—you also must be aware of what’s happening outside the plane. If AR pulls too much attention inside, you could miss something important”. Others agreed that while AR could be helpful for procedural guidance, they were unsure how well it would integrate into real-world flight operations, where missing a critical cue outside the cockpit could have serious consequences. One participant explained, “It provides procedural guidance, but in a real aircraft environment, it could be disorienting by drawing attention away from external surroundings”.

Participants also raised concerns about system reliability, particularly in high-workload situations such as traffic pattern operations, forced landings, or responding to unexpected air traffic conflicts. They noted that any delays or technical inconsistencies in AR responsiveness could disrupt workflow at critical moments, increasing cognitive load when quick decision-making is required. Additionally, some pointed out hardware discomfort, mentioning that the weight and fit of the HMD could cause fatigue during extended flights, further impacting usability. Beyond usability, participants were particularly concerned about system failures, especially in solo flight scenarios, where a malfunctioning AR system could introduce unnecessary distractions or leave them without crucial procedural guidance. One participant cautioned, “If the system fails, you could put yourself in a more dangerous situation”. Given these limitations, many preferred maintaining a low-tech fallback option for in-flight use, emphasizing that conventional paper checklists can be a reliable tool. They explained that while AR could enhance training,

it should not replace well-established methods that pilots can depend on in any situation. As one participant noted, “You still need something to fall back on. AR is great, but it shouldn’t replace what already works”.

Participants widely agreed that these concerns reinforced the idea that AR is best suited for structured, controlled environments such as classroom or simulators. In these settings, its benefits, such as step-by-step procedural guidance and interactive overlays, can be leveraged without the risks associated with in-flight distractions or system failures.

5.5 Discussion

5.5.1 Effectiveness and Limitations of AR-Assisted Training

The NASA-TLX results demonstrated a substantial reduction in perceived workload for AR-assisted training. This reduction is likely attributable to AR’s structured, step-by-step guidance and its interactive interface, which allows participants to interact with instructional overlays directly in their field of view rather than shifting attention between paper-based instructional materials and cockpit controls. By keeping critical procedural information within immediate sight and enabling interaction through hand gestures, AR minimizes cognitive effort and task interruptions, leading to more efficient task execution. This is consistent with cognitive load theory, which posits that externalized guidance systems reduce working memory demands during complex tasks [320,321].

Beyond reducing workload, AR significantly improved situational awareness, as reflected in higher SART scores, suggesting enhancements in information perception, comprehension, and real-time decision-making. This improvement is likely attributable to AR’s ability to integrate task-relevant visual cues directly into the operational environment, reducing the need for participants to shift focus between multiple sources of information. By presenting context-sensitive overlays that highlight critical cockpit instruments and controls, AR likely enhances attentional allocation, accelerates information processing, and improves response accuracy in operational contexts. These findings align with research on situational awareness development, which emphasizes the role of structured external cues in supporting information processing and predictive assessment in dynamic environments [322,323].

The study also found strong user acceptance, as reflected in higher Technology Acceptance Model (TAM) scores. Participants perceived AR as both useful and intuitive, which may be attributed to its structured instructional design, reducing uncertainty and making procedural steps easier to follow. Additionally, AR’s interactive nature enhanced training engagement among early-stage ab-initio student pilots who benefited from visual overlays and step-by-step instructions. These findings align with prior research indicating that user-friendly AR interfaces improve engagement and task efficiency, especially when interactive visual elements guide learners through complex procedures [324,325].

Importantly, the study found no significant difference in simulator sickness levels (SSQ scores) between AR-assisted and paper-based training. While some variability in discomfort levels existed among participants during AR-assisted training, the overall results indicate that AR does not inherently increase sickness symptoms or introduce additional physiological burdens, reinforcing its viability as a training tool. This aligns with prior research suggesting that well-designed AR interfaces can minimize discomfort when visual presentation remains stable and interaction is intuitive [326,327].

Another key advantage of AR-assisted training was a significant reduction in instructor dependence compared to paper-based training, suggesting that its structured, real-time guidance effectively supports procedural execution with minimal external intervention. By integrating immediate, context-sensitive overlays directly into the operational environment, AR likely reduces cognitive effort, minimizes uncertainty, and enables a more seamless transition between learning and execution, resulting in fewer requests for instructor clarification. Additionally, the interactive nature of AR may have strengthened confidence in task execution by providing real-time visual overlays that highlight the correct instruments and control inputs, reinforcing procedural accuracy without requiring verbal confirmation from an instructor. This further supports cognitive load theory, which emphasizes that reducing extraneous cognitive demands—such as searching for instructional references—frees up working memory, allowing for greater focus on task execution [320,321].

Despite these advantages, the study found no significant improvement in knowledge retention for AR-assisted training compared to paper-based instruction. The chi-square test results showed no statistically significant association between training modality (AR vs. paper) and retention outcomes, suggesting that AR does not inherently enhance recall or long-term knowledge application. The slightly higher memory retention errors for AR-assisted training suggest a possible reliance on real-time guidance, potentially reducing active recall and weakening the encoding of procedural steps into long-term memory. In contrast, paper-based training requires participants to interpret, and execute procedural sequences without external cues, potentially fostering stronger retention. These findings align with prior research suggesting that while externally provided cues improve immediate task execution, they can hinder cognitive encoding and recall efficiency [296,298,328]. To improve knowledge retention, AR-based training could incorporate reinforcement strategies that encourage independent cognitive processing. One potential approach is to gradually transition from guided instruction to recall-based learning, reducing dependency on real-time overlays. AR systems could integrate progressive memory-recall phases, where external cues are minimized in later stages of training, requiring student pilots to retrieve and apply procedural knowledge independently. Additionally, post-training debriefings and recall-based exercises could reinforce

procedural knowledge, ensuring student pilots internalize information rather than passively following instructions.

While AR effectively reduced the need for instructor intervention, some participants—particularly those with no prior flight experience—still required direct instructor assistance, especially during landing procedure. Landing is a motor-intensive phase of flight, requiring precise coordination of descent, power management, control inputs and real-time adjustments. Although AR provided structured procedural guidance, it did not fully support the fine motor skill development required for precise aircraft control. Since nearly half of the participants had zero flight experience, they struggled with fundamental motor tasks such as coordinating descent and maintaining glide path stability, where difficulties in adjusting pitch and throttle smoothly led to oscillations during approach. Executing a smooth touchdown also proved challenging, as a number of these participants had difficulty determining the correct timing for the flare, often resulting in hard landings or excessive floating. Additionally, applying rudder after touchdown posed another obstacle, as AR guidance instructed participants to use rudder for directional control, but many overcompensated, leading to excessive yaw and off-centre alignment on the runway. These motor execution challenges required instructor intervention to prevent unsafe landings and loss of control, highlighting AR's limitation in hands-on skill development. Although AR effectively supports cognitive learning, it does not inherently facilitate kinesthetic learning, which is critical for real-world piloting tasks. To support motor skill development, AR-assisted training could incorporate progressive learning strategies that emphasize gradual motor skill acquisition rather than purely procedural execution. This can begin with isolated motor drills, such as throttle modulation and pitch control exercises to improve smooth glide path adjustments, simulated landing drills that refine flare timing and touchdown coordination, and rudder coordination exercises to ensure precise post-touchdown directional control before integrating full landing sequences. As student pilots develop proficiency, AR could transition to a reduced guidance mode, where external cues are gradually minimized, encouraging reliance on internal motor memory and judgment. Furthermore, adaptive scenario training, such as practicing crosswind or short-field landings, can enhance situational adaptability and independent motor execution, ultimately reducing dependence on AR assistance.

Beyond instructional considerations, the study identified several usability limitations related to AR's usability in real-flight conditions. Key challenges included field-of-view constraints, HMD weight, tracking lag, and difficulty shifting focus between overlays and physical environment. Issues with tracking responsiveness, particularly when participants moved their heads rapidly, occasionally disrupted workflow and instructional continuity. Additionally, several participants expressed concerns about AR overlays becoming potential distractions, especially in high-risk scenarios where external situational awareness is critical. Additionally, concerns about system reliability emerged, particularly regarding AR malfunctions

in emergency situations or solo flight conditions, where immediate unaided decision-making is required. While AR enhances structured procedural execution, it may inadvertently compete for cognitive attention, potentially interfering with rapid decision-making and environmental scanning in operational settings. These findings suggest that while AR could be highly effective in structured, ground-based training environments such as simulators and classrooms, its direct application in live-flight scenarios requires further refinement. Ensuring that AR interfaces do not interfere with real-time decision-making and external environmental scanning will be critical for its broader adoption in operational flight training.

Another major consideration is the cost and accessibility of AR implementation. While AR offers clear advantages in structured training environments, high equipment costs, system maintenance, and logistical challenges could hinder widespread adoption, particularly for smaller flight schools. The expense of AR headsets, periodic system updates, and technical support requirements may make AR less feasible for budget-conscious training programs. Additionally, the complexity of setting up, calibrating, and maintaining AR systems could discourage institutions from integrating AR into their curricula, especially if it requires specialized infrastructure. To make AR more accessible, future developments should prioritize reducing costs and improving scalability to enable wider adoption across flight training programs, particularly for smaller flight schools. Potential solutions include developing more compact and cost-effective AR headsets (e.g., smart glasses) to improve affordability, simplifying hardware requirements to reduce the need for specialized infrastructure, and minimizing maintenance costs through streamlined system updates. Additionally, interaction techniques, such as hands-free methods (e.g. gaze-based controls), could enhance ease of use, making AR more intuitive and accommodating for learners with different experience levels and familiarity with technology. While enhancing system response times and incorporating adaptive learning modes primarily focus on usability and training effectiveness, they also contribute to accessibility by ensuring that AR systems function smoothly, efficiently, and without excessive technical barriers. Faster response times can reduce frustration and cognitive overload, making the technology more approachable, while adaptive learning modes that transition from guided assistance to independent execution can accommodate student pilots with different skill levels, ensuring a more inclusive and flexible learning experience. Further, optimizing plug-and-play functionality with existing training devices could help reduce setup complexity and integration costs, making AR more feasible for institutions with limited resources. These improvements collectively could ensure that AR remains a scalable, cost-effective, and user-friendly training tool, lowering both financial and technical barriers to widespread adoption.

Overall, this study highlights AR's potential as a valuable supplement to traditional pilot training, particularly in structured, controlled environments. It can be especially beneficial for ab-initio student pilots

during early-stage instruction, where it can support pre-flight preparation and procedural familiarization by allowing student pilots to review checklists, practice cockpit flows, and develop an understanding of operational procedures before entering a real cockpit. Beyond pre-flight training, AR can serve as a reinforcement tool between dual instruction lessons (pre-solo), allowing pilots to visually and interactively rehearse flight procedures in a structured yet flexible manner. This can help improve procedural fluency, reduce the need for remedial instruction, and maximize efficiency during in-flight training. Furthermore, AR can provide scenario-based reinforcement for emergency procedures, enabling pilots to practice critical responses in a risk-free environment, potentially enhancing preparedness for real-world contingencies. Additionally, AR can enhance aircraft familiarization, helping student pilots explore cockpit layouts and operational differences, which may facilitate smoother transitions between different aircraft types throughout flight training. However, while AR can enhance engagement, procedural accuracy, and training efficiency, its usability limitations and instructional constraints need to be addressed before widespread adoption. Future research can focus on optimizing hardware for better ergonomics and responsiveness, refining instructional design to promote independent learning and recall-based retention, and developing strategies to support motor skill acquisition.

5.5.2 Comparison of Study Insights with Literature

This study reinforces and expands upon prior research on AR-assisted training, confirming its benefits while identifying new insights and limitations.

Building on previous research [23,280,282,283,285], this study further demonstrates that AR reduces perceived workload by providing structured, step-by-step visual guidance, thereby minimizing working memory demands and enhancing procedural efficiency. Additionally, the observed improvement in situational awareness aligns with findings from [23,24,282,284], which highlight how task-relevant AR overlays embedded in the operational environment improve recognition and response to critical operational elements. Moreover, the high TAM scores observed in this study, indicating strong user acceptance of AR-assisted training, are consistent with the findings of [278,288], both of which underscore the role of interactive visual aids in enhancing engagement and making training more intuitive.

A key advantage observed in this study was the reduction in instructor intervention required for participants using AR. While this finding aligns with [25,285], important differences set this study apart. Prior research involved seasoned commercial pilots who were already familiar with the tested flying scenario and had undergone pre-training sessions, ensuring a strong foundation before AR integration. Additionally, AR in those studies functioned as an in-flight assistant, complementing existing training rather than serving as a standalone instructional tool. In contrast, this study evaluated AR's effectiveness

as a fully independent training solution, introduced without prior preparation or structured onboarding—a critical distinction that has been largely overlooked in previous research.

Despite AR's procedural benefits, this study found no significant improvement in knowledge retention with AR, diverging from [24,285]. Unlike prior research, which reported improved procedural recall with AR, this study reveals a potential drawback—while AR enhances procedural execution, it may also contribute to increased memory retention errors due to over-reliance on real-time guidance. This distinct finding underscores the need for reinforcement strategies that transition from guided instruction to independent recall-based learning. Beyond procedural accuracy, this study also highlights AR's limitations in developing fine motor skills, particularly for complex maneuvers like landing. While prior research reported improved landing accuracy [280], it did not fully address motor coordination challenges or acknowledge that AR does not inherently support kinesthetic learning, a gap overlooked in previous studies. By showing that some participants still required instructor intervention despite AR guidance, this study underscores the necessity of supplementing AR with progressive motor skill training strategies, such as isolated motor drills and adaptive scenario-based learning.

This study also expands on prior findings [22,23,25,278,284] on usability constraints and in-flight integration challenges by providing more detailed insights into cognitive trade-offs, system reliability concerns, and the need for AR interface refinements. The findings reinforce that while AR is a valuable tool for structured procedural training in controlled settings like simulators, improvements in system responsiveness, ergonomics, and cognitive load management are necessary before it can be considered for full-scale adoption in live-flight scenarios. Beyond usability, this study raises practical concerns about the cost and scalability of AR implementation, particularly for smaller flight schools. High equipment costs, system maintenance, and logistical challenges could limit widespread adoption—an issue not thoroughly addressed in previous research. However, by identifying potential solutions such as plug-and-play functionality, simplified hardware requirements, and more affordable AR headsets, this study contributes to the ongoing discussion on making AR more accessible for broader training applications.

Overall, this study confirms many of the previously reported benefits of AR-assisted training, including reduced cognitive workload, enhanced situational awareness, and increased user acceptance. However, it introduces new insights by evaluating AR's effectiveness for ab-initio student pilots in general aviation (GA) training, particularly in pre-flight preparation and procedural reinforcement within structured self-guided learning environments. Unlike prior research, which has largely focused on commercial and military training with experienced pilots, this study highlights AR's potential for early-stage flight instruction while also identifying key challenges. To refine AR's role in pilot training, future research should address knowledge retention strategies, motor skill development, usability constraints, and cost-effective

implementation. By systematically comparing these findings with existing literature, this study provides a nuanced perspective on AR's evolving role in pilot training and highlights areas for further refinement.

5.5.3 Implications for GA Pilot Training

The findings highlight several key implications for integrating AR into general aviation pilot training, particularly in early-stage training, procedural reinforcement, emergency response, cognitive load management, and adaptive learning.

Many student pilots struggle with early familiarization with the cockpit and basic procedures, which significantly delays their ability to transition into dual instruction training. Since ab-initio pilots have no prior exposure, they often require extensive time to become comfortable with cockpit instruments, avionics, and flight controls before they can effectively execute basic flight maneuvers. This challenge stems from the complexity of cockpit layout, the high cognitive load associated with operating multiple flight instruments, and the unfamiliarity with procedural execution. This inefficiency increases training costs as students require additional instructor-led sessions before advancing to actual flight exercises. Ideally, flight schools aim to streamline learning by enabling a smooth transition from ground-based training to in-flight execution. However, without an interactive pre-flight preparation system, students struggle to build confidence and procedural familiarity, prolonging their PPL training timeline. AR technology offers a transformative solution by providing immersive, real-time cockpit visualization, allowing students to interact with flight instruments and practice procedural flows before entering an aircraft. Unlike traditional learning methods that rely on static cockpit posters, diagrams, and textbooks, by integrating AR-based cockpit familiarization into early training, flight schools can shift fundamental training from costly instructor-led sessions to efficient, technology-driven pre-flight modules, optimizing learning while reducing costs.

Retaining procedural knowledge is a major challenge in ab initio pilot training, often delaying solo flight progression. Student pilots frequently struggle with structured checklists (e.g., pre-flight inspection, engine start-up, pre-takeoff, and after-landing procedures) and in-flight maneuvers (e.g., takeoffs, turns, stall recovery, and landings), particularly when training sessions are spaced out due to scheduling, weather, or resource constraints. These gaps lead to repetitive review sessions, consuming valuable in-flight dual instruction training time. While "couch flying" (mentally rehearsing procedures) is recommended, its lack of interactivity limits effectiveness. AR-based procedural reinforcement can allow student pilots to practice checklist execution, cockpit flows, and flight maneuvers between lessons without additional flight time. This reduces redundant review flights, lowers training costs, optimizes instructor time, and minimizes fuel consumption and carbon emissions—making training more efficient and sustainable.

Emergency procedures require student pilots to memorize "flows"—sequential hand movements across cockpit controls—since these actions are often absent from formal onboard checklists. Traditionally, students rely on cockpit posters, static diagrams, and instructor briefings to mentally visualize procedures before executing them in a simulator or aircraft. However, this approach lacks tactile interaction and real-time feedback, making it difficult to develop instinctive responses under stress. AR can provide a dynamic alternative by offering real-time visual guidance, spatial awareness, and interactive reinforcement. Unlike static references, AR overlays can enable student pilots to practice emergency procedures with step-by-step prompts and haptic feedback. However, to ensure pilots develop long-term recall and autonomous decision-making skills, AR training must be carefully structured to transition from guided support to independent execution.

Traditional dual instruction in-flight training relies heavily on real-time verbal communication, requiring student pilots to process instructions, control the aircraft, monitor instruments, and scan for external threats simultaneously. This multitasking often leads to cognitive overload, making it difficult to retain instructions, especially under stress. Student pilots may hesitate to ask questions due to fear of judgment, leading to silent misunderstandings that hinder progress. The chaotic cockpit environment further contributes to information loss before post-flight debriefings. AR can mitigate these challenges by shifting learning to structured, self-paced environment, reducing dependency on verbal instruction while ensuring training consistency. By allowing student pilots to internalize flying exercises before live training, AR can enhance confidence, minimize in-flight repetition, and help student pilots enter the cockpit with a stronger foundational understanding.

Student pilots have diverse learning styles, and traditional verbal explanations and real-time instructor guidance may not be effective for those who learn best through visual or hands-on reinforcement. AR can accommodate diverse learning preferences by providing interactive, real-time visual training, ensuring student pilots receive multi-sensory reinforcement tailored to their cognitive and behavioral needs. Additionally, AR can help instructors identify and address learning gaps, such as delayed responses, or poor situational awareness, enabling them to provide more targeted feedback and adaptive training strategies.

5.6 Limitations

This study's participant sample is largely homogeneous, as participants were drawn from a single aviation school at one location. This may limit the generalizability of the findings, as training methodologies, instructor approaches, and institutional resources can vary across different flight schools and geographic regions. Future research should incorporate a more diverse sample from multiple training institutions across

various locations to capture broader perspectives and evaluate the applicability of AR-based training in different learning environments.

The participants in the study had a narrow age range, limited to 18 to 21 years, which may restrict the generalizability of the findings. Cognitive processing, learning preferences, and technology acceptance may vary across age groups. Future research should include a broader age range to assess whether AR-based training is equally effective for older ab initio student pilots and to evaluate its adaptability across diverse learner demographics.

The gender distribution within the participant sample (10 females, 20 males) may not fully capture gender-related differences in AR-based training effectiveness. Cognitive processing, spatial awareness, and technology interaction can vary by gender, potentially influencing training experiences and outcomes. Future studies should aim for a more balanced gender representation to explore potential gender-based variations in AR-assisted pilot training and ensure findings are generalizable across diverse student pilot populations.

The study focused on structured procedural tasks in a high-fidelity flight simulator, which may not fully reflect the dynamic challenges of real-world flight, including adverse weather, high-traffic airspace, and in-flight emergencies. Future research should incorporate these variables to assess how AR-based training influences pilot adaptability, decision-making, and performance in unpredictable conditions.

The study assessed procedural retention shortly after training but did not include delayed post-tests to evaluate the persistence of learning over time. This is particularly relevant given the possibility that initial performance gains may reflect novelty effects associated with AR-assisted training. Future research should incorporate delayed retention assessments—such as 2-week and 4-week post-tests—across all dependent variables to examine the stability of these gains and the extent to which AR-trained student pilots retain proficiency over time. Further investigation is also needed to evaluate how well the skills acquired through AR training transfer to real-world flight conditions.

AR application used in the study was a prototype version that had not undergone multiple rounds of design iteration. As a result, the user experience, interface optimization, and instructional effectiveness may not fully reflect the potential of a refined AR training system. Future research should incorporate iterative design improvements based on user feedback, usability testing, and performance evaluations to enhance the functionality and effectiveness of AR-based training solutions.

The short duration of the study may not have fully accounted for the effects of fatigue and sustained interaction with AR system in the simulator cockpit. In real-world flight training, extended exposure to AR systems may introduce usability challenges related to cognitive load, physical discomfort, and sustained

attentional demands. Future research should examine the long-term impact of AR use over multiple training sessions to assess its effectiveness under realistic workload conditions.

The study relied on subjective post-study performance measures, primarily based on self-reported questionnaires. Future research could incorporate objective evaluation methods, including flight data and performance parameters, to quantitatively assess the effectiveness of AR-based training. Additionally, collecting physiological and body movement data, such as electromyography, pupillary response, and heart rate, could provide deeper insights into cognitive workload, stress levels, and motor coordination, offering a more comprehensive understanding of AR's impact on pilot training.

While the study used validated quantitative instruments to assess workload, situational awareness, acceptance, and physiological symptoms, the interpretation of these measures is still grounded in participants' subjective experiences within a specific experimental setting. As such, the insights generated reflect participants' perceptions of cognitive and instructional effectiveness under controlled conditions, which may not fully represent operational realities in varied flight training environments. These findings offer valuable evidence of AR's instructional potential, but further work is needed to assess how these effects translate to more complex or real-world training scenarios over time.

While the study utilizes standardized training scenarios to assess participant experiences, it does not explore instructors' perspectives on AR-based training. Instructors play a critical role in training delivery, adaptation, and student evaluation, and their insights will be vital for understanding how AR can complement and enhance pilot training while maintaining alignment with established instructional practices. Future research could examine instructor perceptions, assessing how AR integration may affect teaching methodologies, student engagement, and overall training effectiveness. Additionally, investigating instructors' views on AR's usability, potential challenges, and its role in supplementing traditional instruction could provide valuable insights for optimizing its implementation in flight training programs.

5.7 Conclusion

This study highlights AR-assisted training as a promising supplement to traditional pilot training methods, particularly in structured environments for early-stage instruction. By supporting pre-flight preparation, procedural reinforcement, emergency response training, and individualized learning, AR has the potential to enhance ab initio general aviation pilot training. Its ability to optimize instructor time, minimize cognitive overload, and provide a more adaptive learning experience can make training more efficient, accessible, and environmentally sustainable, ultimately reducing reliance on costly in-flight training hours. However, for AR to be seamlessly integrated into broader pilot training programs, existing usability limitations and instructional constraints must be addressed. Additionally, further research is needed to explore and establish

effective implementation strategies that align with established training methodologies. Instructor perspectives should also be investigated to understand their attitudes, potential challenges, and best practices for AR adoption. These insights will be paramount in ensuring AR's successful integration as a mainstream training tool in general aviation education.

Chapter 6 (Study 5)

Evaluating Augmented Reality as an Assistive Training Tool for Ab Initio General Aviation Pilots: An Empirical Real-Aircraft Study

6.1 Introduction

In today's rapidly evolving technological landscape, general aviation (GA) pilot training, traditionally dominated by instructor-led, one-on-one in-flight lessons, faces a critical juncture [4,5,329–332]. While this approach has served the industry well for decades by providing personalized instruction and hands-on experience, it is now being challenged by technological advancements reshaping educational practices. The heavy reliance on in-flight training, the cornerstone of traditional methods, is increasingly under scrutiny due to its escalating costs, operational inefficiencies, and environmental impact [1–5,333–335]. At its core, the conventional training model places a significant emphasis on actual flight hours, which, while offering real-world experience, leads to high fuel consumption, carbon emissions, and financial strain. This overreliance burdens both student pilots and flight schools—not only driving up costs but also straining critical resources, including aircraft availability, airspace access, and qualified instructor supply.

Amid growing environmental concerns and the global push for sustainability, the aviation industry is actively seeking innovative and eco-friendly training solutions. Developments such as fuel-efficient and electric aircraft, alternative fuels, and digital training tools are emerging as viable alternatives to address inefficiencies inherent in conventional methods [336–340]. These innovations have the potential not only to reduce operational costs but also to align pilot training with broader sustainability goals by reducing its environmental footprint.

Among digital innovations, transformative educational aids such as Flight Simulation Training Devices (FSTDs) and immersive technologies like Virtual Reality (VR) and Augmented Reality (AR) are reshaping aviation education [341–349]. By replicating real-world flight conditions, these tools offer immersive, hands-on learning experiences that can supplement traditional instruction, while also presenting the possibility of reducing the financial and environmental impact associated with in-flight training. AR, in particular, distinguishes itself through its ability to overlay digital information onto the real world via wearable devices, creating a mixed-reality training environment that can enhance cognitive processing and support practical skill development. The widespread application of AR is demonstrated across various industries—ranging from military operations to healthcare and education—reinforcing its potential for training [26,284,288,289]. The increasing affordability and accessibility of AR devices further strengthen its appeal for integration into training programs [350–352]. Despite its advantages, AR adoption in GA

remains limited. Unlike other sectors of civil aviation—such as commercial and military flight training, where advanced instructional tools are widely embraced—general aviation remains rooted in conventional training methods. [1,2,4,5,26]. This inertia largely stems from GA's traditionally conservative stance and rigid regulatory framework, which collectively hinder motivation and flexibility for adopting emerging technologies.

To bridge the gap between traditional practices and modern advancements, this study evaluates the efficacy of AR as an assistive training technology for GA pilot training. Focusing on ab initio training for novice fixed-wing airplane pilots, it investigates how AR, delivered through a wearable Head-Mounted Display (HMD), impacts training outcomes. By collecting empirical data and analyzing student perceptions, this research aims to assess the feasibility of integrating AR into GA airplane pilot training programs. Ultimately, the study seeks to drive innovation, enhance training efficiency, and support sustainable advancements in GA airplane pilot education.

6.2 Literature Review

This review examines AR as a tool for improving pilot training, drawing insights from peer-reviewed journal articles and conference proceedings. The selected studies prioritize experimental research with robust data collection methods, utilizing both quantitative and qualitative assessments to measure AR's impact. While this study focuses specifically on ab initio training for airplane pilots pursuing a Private Pilot License (PPL) within general aviation, the literature review takes a broader approach by examining AR's potential across other sectors of civil aviation, including commercial and military aviation. By integrating insights from diverse training contexts, this comprehensive review aims to uncover findings that may indirectly inform and enhance ab initio pilot education.

Several studies have examined AR's role in improving procedural accuracy and skill development. Alce et al. investigated AR-based virtual instrument panels for training twenty-seven commercial aviation student pilots on the pre-takeoff flow pattern, reporting a moderate recall accuracy, low workload (NASA-TLX), and high usability (SUS), reinforcing AR's effectiveness in cognitively demanding tasks [278]. Similarly, Schaffernak et al. demonstrated that AR-assisted instruction enhanced landing approach performance in three novice pilots using a light aircraft simulator, as evidenced by movement-based performance assessments and pilot feedback on usability [280]. Expanding their study, Schaffernak et al. incorporated additional workload and engagement assessments (NASA-TLX, SART, PANAS, and QCM) with fourteen novice pilots, finding that while overall performance differences were not statistically significant, AR engagement correlated with post-training improvements [282]. Additionally, Arjoni et al. tested AR's potential for military formation training with five novice pilots in a robotic motion simulator,

replacing the lead aircraft with a virtual projection, which proved effective for procedural learning by enabling pilots to practice maintaining alignment and proper distance while ensuring overall performance remained unaffected [21].

AR has also been explored as a tool to enhance pilot decision-making, particularly in demanding flight scenarios. While much of this research centers on operational assistance, it also highlights AR's training potential by improving situational awareness, reducing cognitive workload, and improving pilot performance in managing high-precision flight operations. Li et al. examined landing scenarios with twenty commercial pilots, integrating an AR-simulated primary flight display into Microsoft Flight Simulator X, finding that AR-supported visual cues reduced workload, shortened fixation durations, and improved pilots' response to critical mode changes [283]. Extending this research, Li et al. examined AR-enhanced landing configuration checks in a Boeing 747 simulator with thirty-four commercial pilots, demonstrating improved situational awareness (SART) and reduced cognitive workload (NASA-TLX) [284]. Similarly, Minaskan et al. found that AR improved situational awareness and lowered cognitive workload (SART, NASA-TLX) in complex landing scenarios using a high-fidelity Airbus A320 simulator with eighteen commercial pilots [23]. Tran et al. investigated AR-assisted guidance in an emergency engine fire simulation with twelve Airbus A320 pilots, showing that AR reduced reaction times, lowered perceived workload (NASA-TLX), and received high usability ratings (SUS), reinforcing its effectiveness in emergency response training [25]. Pérez et al. developed an AR-assisted checklist tool for high-workload conditions, finding that its use in an Airbus A320 simulator with six commercial pilots reduced errors, enhanced procedural reliability, and alleviated cognitive demands, particularly during pre-landing checklists [285].

Beyond flight simulations, AR has been explored as a tool for foundational pilot education. Fächer et al. and Northrup et al. investigated smartphone-based AR training with an unspecified set of novice pilots, focusing on early-stage skill development [286,287]. Fächer et al. found AR effective for cockpit familiarization and engine start procedures, demonstrating strong realism and instructional value. Meanwhile, Northrup et al. examined an AR tool for air traffic control (ATC) communication training, finding it engaging and effective for enhancing communication proficiency. Meister et al. introduced a smartphone-based AR tool to improve meteorology training, specifically in understanding thunderstorm development and associated hazards [288]. Tested with six participants, including seasoned aviation professionals and student pilots, the tool demonstrated strong realism, usability (SUS), and enhanced comprehension of thunderstorm dynamics while maintaining low workload (NASA-TLX). Kim et al. extended AR's instructional tools by developing an AR authoring application for flight instructors to create interactive ground training lessons [289]. Tested by thirty-seven seasoned flight instructors, the application

demonstrated high usability (SUS), and low cognitive workload (NASA-TLX), highlighting its intuitiveness for modernizing flight instruction.

While AR has shown promise as a training tool, significant gaps remain, particularly in its application to GA. Most studies have focused on commercial and military aviation, leaving its role in GA pilot training largely unexplored. Given GA aircraft's smaller size, less complex instrumentation, and distinct operational requirements, AR-based training has potential in this sector, yet research remains limited, especially in ab initio training where foundational flight skills are developed. Additionally, many studies have prioritized operational support rather than comprehensive training integration. Even among training-focused studies, isolated aspects of flight are examined rather than evaluating full procedural workflows. Ground school applications have also been explored in a fragmented manner, with limited consideration for AR's potential in delivering end-to-end instructional experiences. Comparative research evaluating AR's effectiveness against traditional training methods is scarce, and research on AR's impact on knowledge retention remains limited. Technological limitations present additional challenges. Many studies rely on outdated AR hardware or simulated AR environments that do not fully replicate the immersive experience of modern AR systems. Static visualizations remain prevalent, failing to capture the dynamic complexity of real-world flight operations. In some studies, the use of performance metrics that are not aligned with established human factors constructs raises concerns about the validity and reliability of their evaluations. Scalability is another key concern, as the feasibility of AR tools for GA flight schools remains largely unexplored, leaving uncertainties about their practicality, cost-effectiveness, and integration into existing training frameworks. Moreover, most studies have prioritized experienced pilots, with limited focus on novice learners, often using small or undefined sample sizes that restrict generalizability. Perhaps the most critical limitation is the overreliance on simulation-based testing; while simulators provide valuable insights, they cannot fully replicate naturalistic flight conditions such as environmental variability, dynamic decision-making, and physical aircraft handling.

To address these gaps, this study focuses on ab initio training for novice GA student pilots, specifically designed to meet the needs of early-stage flight instruction. Unlike previous research that relied solely on simulated environments, this study will be conducted using an actual airplane rather than a simulator, ensuring a more realistic and comprehensive assessment of AR's impact on pilot training. This transition from simulation-based research to real aircraft trials is necessary for evaluating AR's effectiveness in real-world flight operations. Taking a holistic approach, this investigation examines AR's role within the full procedural context of flight operations rather than isolating specific procedures. By comparing AR-enhanced training with traditional paper-based method, it aims to provide empirical evidence on AR's effectiveness using validated human factors constructs in naturalistic conditions. Additionally, the study

assesses memory retention after AR-based training, addressing prior research suggesting that retention outcomes with AR may not be as strong as those observed with traditional methods. Unlike prior AR training systems that relied on static visuals, this study incorporates dynamic procedural guidance using upgraded AR hardware, enhancing situational awareness and enabling interactive task execution for a more immersive and adaptable training experience. A robust evaluation framework—including post-study questionnaires, certified flight instructor assessments, and semi-structured participant interviews—will ensure a thorough assessment of AR’s potential as a training tool. By systematically addressing these research gaps, this study seeks to advance AR integration into ab initio pilot training, paving the way for more effective, scalable, and industry-relevant training solution for general aviation.

6.3 Methodology

6.3.1 Apparatus

This study was conducted at the Waterloo Wellington Flight Centre (WWFC) in Ontario, Canada, utilizing two commonly used training aircraft from their fleet: the Cessna 172 Skyhawk and the Piper PA-28R-201 Arrow. These aircraft were selected for their widespread use in pilot training and their complementary design features, which cater to different levels of training complexity [353,354]. The Cessna 172 Skyhawk is a high-wing, single-engine aircraft known for its stability, predictable handling, and forgiving flight characteristics, making it well-suited for primary flight training. It has a fixed landing gear with a tricycle configuration—a nose wheel and two main wheels—which enhances ground stability and simplifies taxiing, takeoff, and landing for student pilots. In contrast, the Piper PA-28R-201 Arrow is a low-wing, single-engine aircraft designed for more advanced training. It features retractable landing gear and a constant-speed propeller, providing exposure to complex aircraft operations, such as landing gear management and variable-pitch propeller control, which are essential for transitioning to higher certification levels.

To support AR-based training, the Microsoft HoloLens 2 was used. This mixed reality HMD offers high-resolution see-through lenses (1440×936 pixels per eye) with a 52-degree diagonal field of view (FoV), providing sharp, immersive visuals [294]. The device incorporates spatial mapping, hand and eye tracking, voice commands, and gesture controls to enable seamless interaction with digital content. A suite of advanced sensors ensures precise spatial awareness, including those for motion tracking, head and eye movement detection, depth perception, and ambient light adaptation. Additionally, built-in spatial sound speakers enhance immersion, while its ergonomic, adjustable design ensures comfort. A flip-up visor allows users to transition easily between AR content and the real-world environment.

A custom AR application was developed for the HoloLens 2 to provide real-time augmented cues. Built with the Unity 3D engine, the application utilized AR development tools and libraries to enable spatial mapping, ensuring precise positioning and seamless integration of augmented elements within the physical environment. Interaction was facilitated through two modes: distant overlays were controlled via hand rays and air tap gestures, while closer overlays supported direct fingertip touch for a more tactile experience. User-specific calibration was performed to ensure accurate alignment of augmented elements within the physical environment, optimizing usability and consistency.

6.3.2 Study Setup

This study utilized a within-subject design to compare the effectiveness of two training methods: a paper-based method (PBM) and an AR-assisted method (ARM) delivered via a HMD. The PBM required participants to follow written step-by-step instructions, serving as the baseline condition and reflecting standard pilot training practices. In contrast, the ARM provided real-time visual overlays within the participant's field of view, enabling interactive, hands-free guidance. These AR overlays highlighted key elements in the operational environment, ensuring accurate and sequential execution of the assigned training task.

A pre-flight inspection task was developed in collaboration with a Certified Flight Instructor (CFI) to evaluate performance across both training methods. The procedural steps were derived from the single engine airplane training manual to ensure alignment with standard real-world pre-flight inspection practices [355,356], with the aircraft stationary on a flat surface. This procedure, outlined in Table X, was selected for its practical significance as a pre-flight standard necessary for safe aircraft operation. The study was conducted in the airplane parking area at the WWFC, with conditions carefully monitored to ensure optimal visibility, comfortable temperatures, minimal background noise, and an unobstructed inspection area, maintaining procedural consistency.

To ensure a balanced comparison between training methods, the study incorporated two variations of the pre-flight inspection task, systematically varying both the aircraft type and training method. In Task 1 (T1), participants conducted a pre-flight inspection on a Cessna 172 Skyhawk, while in Task 2 (T2), they inspected a Piper PA-28R-201 Arrow. A Latin square design was implemented to counterbalance the order of task conditions (T1 vs. T2) and training methods (PBM vs. ARM) across participants. By alternating conditions in a structured sequence, this approach mitigated order effects and biases, ensuring a fair and unbiased evaluation of training effectiveness.

Table 12. Detailed steps for pre-flight inspection procedure [355,356]

Step 1: CABIN 1. Control Wheel Lock - REMOVE.
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2. Ignition Switch - OFF.
3. Avionics Power Switch - OFF.
4. Master Switch - ON.
5. Fuel Quantity Indicators - CHECK QUANTITY.
6. Master Switch - OFF.
7. Baggage Door - CHECK

Step 2: EMPENNAGE

1. Rudder Gust Lock - REMOVE.
2. Tail Tie-Down - DISCONNECT.
3. Control Surfaces - CHECK freedom of movement and security.

Step 3: RIGHT WING Trailing Edge

1. Aileron - CHECK freedom of movement and security
2. Flap - CHECK freedom of movement and security

Step 4: RIGHT WING

1. Wing Tie-Down - DISCONNECT.
2. Main Wheel Tire - CHECK for proper inflation.
3. Fuel Quantity - CHECK VISUALLY for desired level.
4. Fuel Filler Cap - SECURE.

Step 5: NOSE

1. Engine Oil Level - CHECK for less than four quarts.
2. Propeller and Spinner - CHECK for nicks and security.
4. Landing Light(s) - CHECK for condition and cleanliness.
5. Carburetor Air Filter - CHECK for restrictions by dust or other foreign matter.
6. Nose Wheel Strut and Tire - CHECK for proper inflation.
7. Nose Tie-Down - DISCONNECT.
8. Static Source Opening (left side of fuselage) - CHECK for stoppage.

Step 6: LEFT WING

1. Main Wheel Tire - CHECK for proper inflation.
2. Fuel Quantity - CHECK VISUALLY for desired level.
3. Fuel Filler Cap - SECURE.

Step 7: LEFT WING Leading Edge

1. Pitot Tube Cover - REMOVE and check opening for stoppage.
2. Fuel Tank Vent Opening - CHECK for stoppage.
3. Stall Warning Opening - CHECK for stoppage.
4. Wing Tie-Down - DISCONNECT.

Step 8: LEFT WING Trailing Edge

1. Aileron - CHECK freedom of movement and security
2. Flap - CHECK freedom of movement and security

6.3.3 Participants

A power analysis using GPower 3.1.9.6 tool determined that at least nineteen participants were required for statistical power [295]. The analysis was set for a paired-sample t-test with an effect size of 0.8 (Cohen's d) and an alpha level of 0.05. The effect size was based on prior studies examining AR applications in learning and skill development [296,298,357–364]. To ensure statistical robustness and account for variability, the final sample size was set at twenty participants.

Twenty student pilots (9 females, 11 males) from the WWFC PPL program were recruited through study advertisements at the training facility. Recruitment targeted student pilots in the early stages of training

with minimal flight experience, a stage where students are typically introduced to pre-flight inspections but have not yet gained routine familiarity or independent execution skills. Participants averaged 19.7 years in age and 2.8 flight hours ($SD = 2.2$). Although participants had been introduced to the pre-flight inspection procedure during their initial flight lessons, their exposure was limited to instructor-led demonstrations or supervised completion, with no independent practice or procedural memorization. As a result, they neither developed proficiency nor internalized the procedural steps, minimizing the influence of prior experience on task performance. No participants had previous exposure to AR technology, ensuring a neutral and uniform experience with AR throughout the study. Participation was voluntary, and each participant received a fixed payment as compensation.

Each participant spent about an hour and a half in the study, structured into two phases. The first twenty minutes focused on orientation, where participants reviewed an information letter detailing the study's purpose, rights, and data collection process. They had the opportunity to ask questions and were reminded of their right to withdraw at any time before providing informed consent. Data confidentiality was upheld through anonymized records. A familiarization session followed to introduce both training methods. Participants first explored the AR method, learning to interact with digital overlays using hand gestures. Next, they practiced following step-by-step written instructions with the paper-based method. This structured introduction ensured participants were equally acquainted with both methods before proceeding to the training task. The remaining time was dedicated to performing the pre-flight inspection, both with and without training aids. The study received ethical approval from the University of Waterloo's Research Ethics Board (#46392) and was conducted in full compliance with the board's ethical standards and regulations.

6.3.4 Procedure

The study followed a structured approach to ensure consistency and comprehensive data collection across all participants, with the process outlined as follows: 1) Participants received a briefing on the study's purpose, objectives, training methods (PBM and ARM), participation expectations, data confidentiality, and safety measures. They reviewed an information letter, asked questions, and provided informed consent. 2) Participants completed a pre-study questionnaire to collect demographic and professional background details. 3) Participants underwent practical exposure to both training methods, followed by AR-integrated HMD calibration at the airplane parking area. 4) Participants were briefed on the training tasks (T1 and T2) and then performed them, with a Latin square design ensuring a varied task order. A modulating task was introduced between training tasks to reduce cognitive load and carryover effects. 5) A Certified Flight Instructor (CFI) accompanied participants during each training task, assisting as needed and documenting the support provided. To maintain consistency, the CFI underwent the same briefing and consent process.

Figure 22 illustrates a participant performing T1 with PBM and T2 with ARM, and Figure 23 shows examples of AR overlays aiding empennage and wing inspections during T2. 6) After completion of training tasks, participants provided feedback through post-study questionnaires and semi-structured interviews on their experiences, challenges, and perceptions. Interview questions are listed in Table 11. 7) After a brief 10-minute break, participants completed a retention assessment exercise by repeating both training tasks without assistance from either training method. A CFI observed and evaluated their performance in each exercise to assess skill retention. Each training task lasted slightly over 15 minutes, while the retention assessment exercise was completed in under 40 minutes.



Figure 22. Participant performing T1 with PBM (top) and T2 with ARM (bottom)

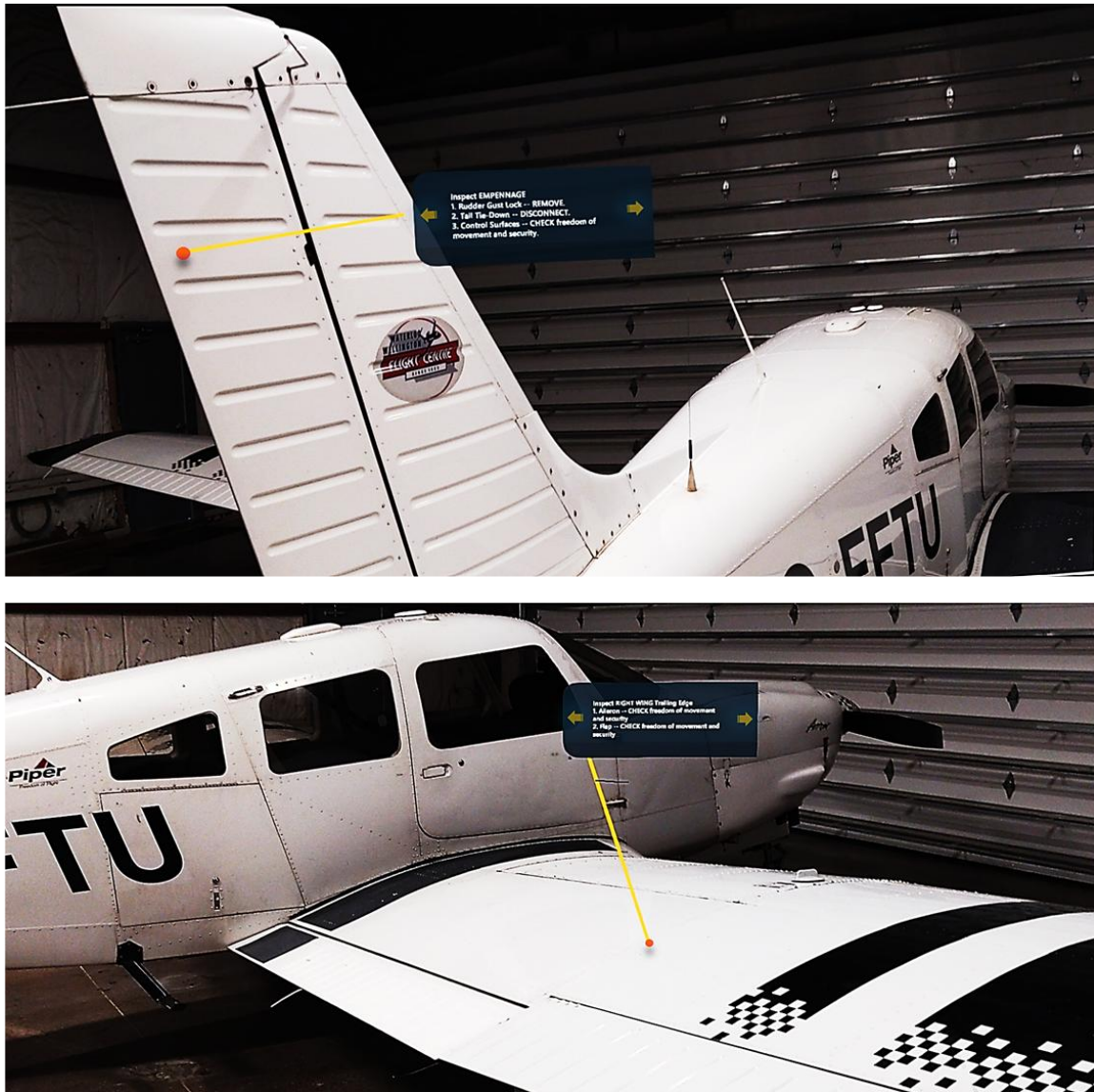


Figure 23. AR overlays assisting with the steps involving empennage (top) and right-wing inspection (bottom) during T2

Table 13. Semi-structured interview questions

1. How would you compare AR-based instruction to paper-based training?
Follow-up: What specific advantages or drawbacks did you notice?
2. How can AR-based instruction enhance student pilots' proficiency?
Follow-up: Are there specific flight procedures where AR offers a clear advantage?
3. Did you face or do you anticipate any usability issues with AR-based training?
Follow-up: If yes, what improvements would enhance its effectiveness or usability?
4. Would you consider AR-based method for future training?
Follow-up: What influenced your choice?

6.3.5 Evaluation Method

Participant experiences and performance across the two training methods (PBM and ARM) were assessed using seven dependent variables (DVs): mental workload, situational awareness, user acceptance, sickness, instructor-provided assistance, retention recall errors, and overall retention performance. Four DVs—mental workload, situational awareness, user acceptance, and sickness—were measured immediately after each training task using standardized post-study questionnaires. Instructor-provided assistance was recorded during training task to assess participants' reliance on external support, while retention recall errors and overall retention performance were evaluated during the retention assessment exercise, where participants independently completed both training tasks (T1 and T2).

Mental workload was assessed using the NASA Task Load Index (NASA-TLX), which evaluates performance, effort, frustration, and mental, temporal, and physical demand [304,306]. Participants rated each dimension on a 1–100 scale, with scores averaged to produce a composite workload score (0–100), where higher values indicated greater cognitive demand. Situational awareness was measured using the Situation Awareness Rating Technique (SART-10D) [301,309]. This 10-item scale assessed attentional demand, supply, and understanding, with scores calculated using the formula $\text{Understanding} - (\text{Demand} - \text{Supply})$, producing values between -7 and 14. Higher scores indicated stronger situational awareness. User acceptance was evaluated using the Technology Acceptance Model (TAM) [311,313], which measures perceived usefulness (PU) and perceived ease of use (PEOU). Participants rated 12 items on a 7-point Likert scale, with combined subscale scores ranging from 1 to 7, where higher values indicated greater usability and acceptance. Sickness was assessed using the Simulator Sickness Questionnaire (SSQ). Initially designed for flight simulators, the SSQ is now commonly applied across both immersive and non-immersive environments [315,316]. This 16-item tool categorized symptoms into nausea, oculomotor strain, and disorientation. Ratings (0–3) were weighted (nausea: 9.54, oculomotor: 7.58, disorientation: 13.92) and summed, with the Total Score (TS) calculated by multiplying the sum by 3.74 (max: 300). Higher scores indicated more severe sickness.

Instructor-provided assistance, retention recall errors, and overall retention performance, recognized as measures of training effectiveness [300], provided additional insights into participant performance. Instructor-provided assistance was recorded to evaluate participants' ability to complete training tasks independently, categorized as zero assists (independent completion) or assisted (guidance provided without direct instruction). Retention recall errors were tracked as deviations from expected procedural steps during the retention assessment exercise, with all errors counted to assess procedural accuracy. Overall retention performance was classified into three categories: Complete Success (task completed accurately without errors), Partial Success (task completed with errors), and Failure (task not completed). A Certified Flight

Instructor (CFI) conducted all retention assessments following standardized Transport Canada Flight Test Guide for PPL criteria [317], ensuring consistency. To prevent bias, the CFI was blinded to the training method participants previously used for the respective training tasks.

6.3.6 Analytical Approach

The study assessed the effects of two training methods (PBM and ARM) on all dependent variables (DVs) using descriptive and inferential statistics. Shapiro-Wilk tests checked normality. Paired samples t-tests analyzed normally distributed data, while the non-parametric Wilcoxon signed-rank test was used for non-normal distributions. Statistical significance was set at $\alpha = 0.05$. Effect sizes were measured using Cohen's d for normally distributed data and Cliff's Delta for non-normal data [318,365]. Bayesian paired samples t-tests were conducted for further validation when no significant differences were found. As overall retention performance outcomes were categorical, they were analyzed using the Fisher's exact test. Additionally, insights from the semi-structured interviews were examined using thematic analysis.

6.4 Results

An evaluation of NASA-TLX, SART, TAM, SSQ, instructor-provided assistance, retention recall errors, and overall retention performance provided key insights into the strengths and limitations of AR and Paper-based training methods.

Participants reported significantly lower workload with AR training compared to paper-based training method. The mean NASA-TLX score for AR training was 46.5 (SD = 7.85), whereas for Paper training, it was 67.9 (SD = 15.1). The Shapiro-Wilk test confirmed the normality of paired differences ($W = 0.94$, $p = 0.27$), supporting the use of parametric analysis. A paired t-test revealed a significant difference ($t(19) = -5.99$, $p < 0.001$), with a large effect size (Cohen's $d = 1.34$) for the paired data, indicating that participants experienced a substantial reduction in workload when trained with AR. The SART analysis indicated higher situational awareness with AR training compared to the paper-based training method. The mean SART score was significantly higher for AR (6.08, SD = 1.08) than paper (3.12, SD = 0.98). The Shapiro-Wilk test of paired differences confirmed normality ($W = 0.96$, $p = 0.52$). A paired t-test revealed a highly significant difference ($t(19) = 9.29$, $p < 0.001$). The large effect size for paired data (Cohen's $d = 2.08$) underscores the practical advantage of AR training in enhancing situational awareness. Similarly, the TAM analysis indicated higher user acceptance of AR training compared to the paper-based training method. The mean TAM score for AR was 4.95 (SD = 0.47), compared to 3.01 (SD = 0.46) for Paper. The Shapiro-Wilk test ($W = 0.95$, $p = 0.33$) verified normality of paired differences, and a paired t-test confirmed a highly significant difference ($t(19) = 11.19$, $p < 0.001$). A large effect size for paired data (Cohen's $d = 2.5$) emphasized the substantial advantage of AR training in terms of perceived usefulness and ease of use.

Conversely, the SSQ analysis revealed no significant difference in simulator sickness symptoms between the AR and paper-based training methods. The mean SSQ score was slightly higher for AR training (141.12, SD = 118.28) than paper training (126.86, SD = 152.44). The Shapiro-Wilk test confirmed normality of paired differences ($W = 0.96$, $p = 0.62$). A paired t-test found no significant difference ($t(19) = 0.51$, $p = 0.62$). A Bayesian paired t-test ($BF_{10} = 0.26$) further reinforced these findings, indicating no substantial difference between the two training methods. The Bayesian effect size (median = 0.09, 95% credible interval: [-0.31, 0.51]) and a small Cohen's d (0.11) effect size for paired data confirmed that AR training and Paper training have comparable effects on simulator sickness symptoms. These findings are summarized in Figure 24.

Participants who underwent AR training needed significantly less instructor assistance during training tasks than those trained with the paper-based method ($M = 0.2$, $SD = 0.52$ vs. $M = 1.9$, $SD = 1.71$). The Shapiro-Wilk test revealed a non-normal distribution of the paired differences ($W = 0.8$, $p < 0.001$), necessitating a Wilcoxon signed-rank test, which confirmed a significant reduction in instructor assistance for AR compared to paper ($W = 0$, $p < 0.001$). Given the non-normality, Cliff's Delta was used as the effect size measure, yielding a large effect ($\delta = 0.75$). This result highlights the practical advantage of AR training in fostering participant independence (Fig. 6). During the retention assessment exercise, AR trained participants made slightly more errors ($M = 2.9$, $SD = 1.76$) compared to those with Paper training ($M = 2.55$, $SD = 1.88$). The Shapiro-Wilk test confirmed normality of paired differences ($W = 0.91$, $p = 0.06$). A paired t-test found no significant difference ($t(19) = 0.83$, $p = 0.42$), and a Bayesian paired t-test ($BF_{10} = 0.35$) further reinforced this conclusion. The Bayesian effect size (median = 0.19, 95% credible interval: [-0.22, 0.61]) and Cohen's d (0.18) suggested only a small practical difference, meaning the additional errors in AR training were not statistically or practically meaningful. These findings are summarized in Figure 25. A Fisher's Exact Test assessed the relationship between training methods (AR vs. Paper) and overall retention performance (Complete Success, Failure, Partial Success), with observed frequencies shown in Figure 26. Given the categorical nature of the data, Fisher's Exact Test was the appropriate choice. The test yielded an odds ratio ($OR = 0.3$), $p = 0.61$, indicating no significant association between training method and overall retention performance. This suggests that variations in retention performance were likely due to random chance rather than the training method.

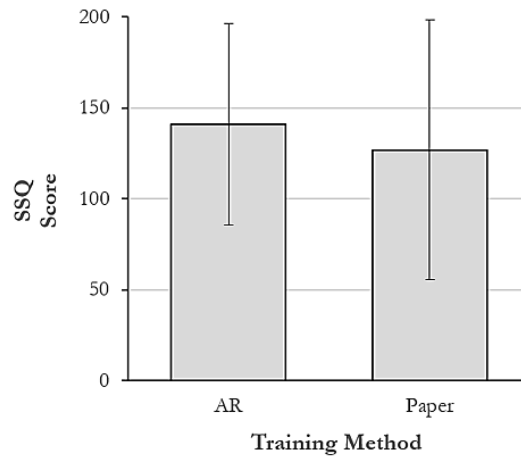
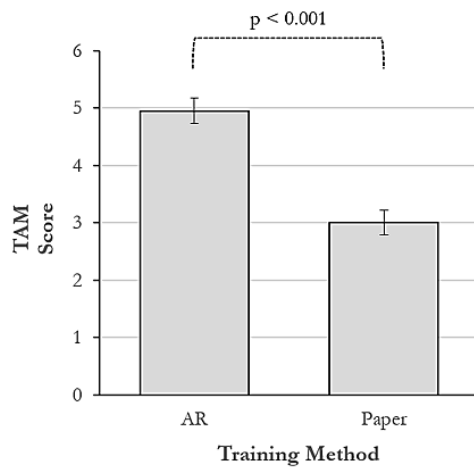
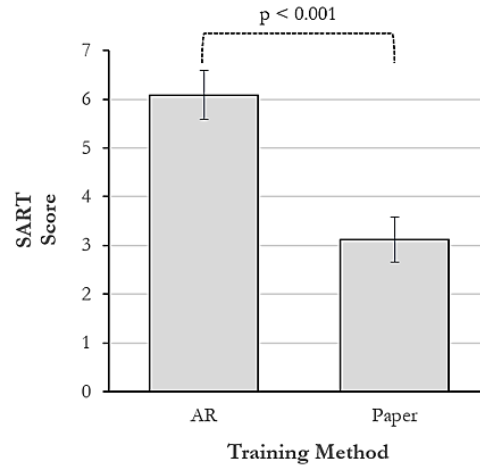
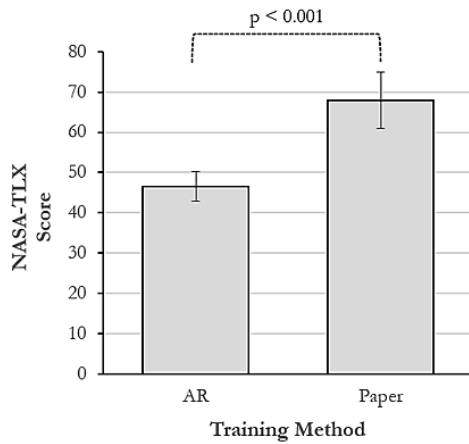


Figure 24. Comparison of training modalities (AR vs. paper) for NASA-TLX (top left), SART (top right), TAM (bottom left), and SSQ (bottom right). Error bars represent 95% confidence interval.

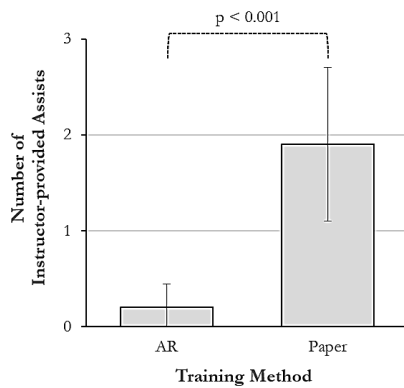


Figure 25. Comparison of training methods (AR vs. paper) for instructor-provided assists (Error bars represent 95% confidence interval).

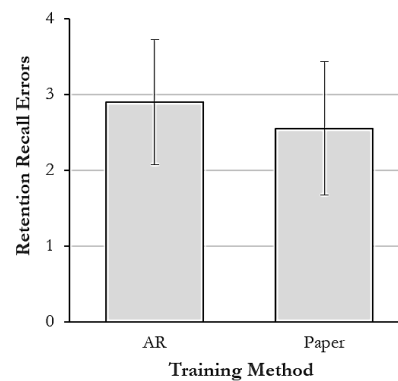


Figure 26. Comparison of training methods (AR vs. paper) for retention recall errors (Error bars represent 95% confidence interval).

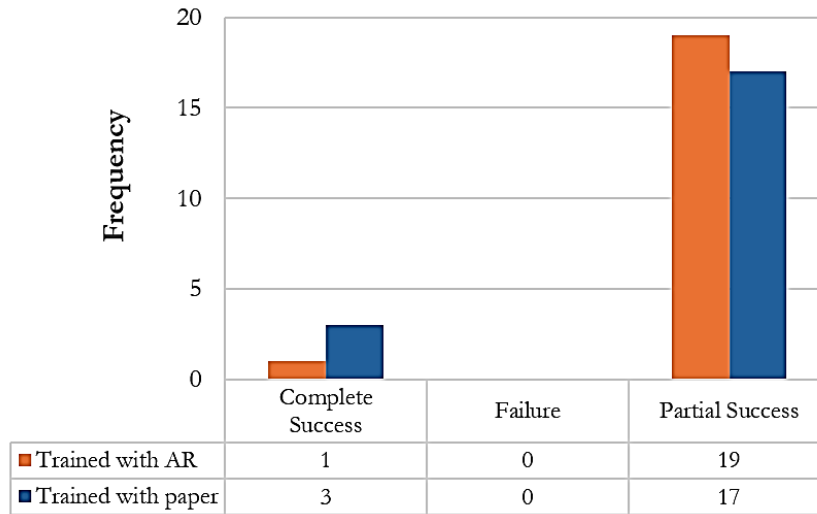


Figure 27. Observed frequencies of overall retention assessment outcomes among all participants.

The semi-structured interview responses, which investigated participants' experiences, perspectives, and challenges with training methods, were analyzed using thematic analysis following Braun et al.'s framework [319]. To enhance reliability, two researchers independently reviewed the data, applying both deductive and inductive coding strategies. Deductive coding was structured around established theoretical frameworks, categorizing the data into predefined themes based on existing literature: AR Technology in Pilot Instruction [21,23,280,282,283,285,286,348] investigates how AR technology can be incorporated into pilot training to enhance learning experiences and skill acquisition. Guided Procedural Learning [2,280,285,286,296,298,362,363] focuses on AR's ability to offer structured training designed to improve accuracy, consistency and skill advancement. AR's Impact on Retention and Independent Learning [289,296,298,300,351,363] assesses AR's effectiveness in promoting knowledge retention, and its potential to facilitate interactive, self-directed learning while reducing dependence on instructors. Using a data-driven approach, inductive coding allowed themes to emerge naturally from participant responses, facilitating the discovery of unanticipated insights. These emerging themes included Cost-Effective Reinforcement, which highlighted AR's potential to support traditional instructor-led training for both foundational and advanced procedural learning while considering cost-effectiveness concerns; Skill Progression and Autonomy, which focused on the shift from instructor-led training to independent learning, promoting confidence and self-sufficiency; and Challenges and Constraints, which highlighted issues related to in-flight implementation, ergonomic considerations, and limitations arising from extended use. This analysis identified three interconnected themes: AR Potential for Early-Stage Training, which examines AR's role as a structured reinforcement tool in early flight training while recognizing its limitations for real-flight application; Potential Use Cases for AR, which explores how AR can support pre-

flight preparation, enhance procedural accuracy, and strengthen procedural memory in controlled training environments; and Considerations for Usability, Integration, and Adoption, which addresses key challenges such as hardware usability, system responsiveness, affordability, and overall practicality in flight training environments. The findings under each theme are presented below, derived exclusively from participant feedback, without any analysis or input from the authors.

AR Potential for Early-Stage Training

Participants raised concerns about using AR for in-flight training, particularly visual obstructions, cognitive distractions, the risk of over-reliance on technology, and technological reliability. Some noted that AR overlays within their field of view could interfere with external traffic monitoring, making it harder to track other aircraft. One participant explained, “You already have so much to focus on when flying. If you add AR instructions in the field of view, it could actually become a distraction instead of a help”. Others pointed out that wearing an AR headset could limit peripheral vision, which is critical for monitoring the horizon, especially for those who wear glasses. Additionally, cognitive distractions were a concern, as some participants felt that intrusive AR overlays could divert attention from essential cues such as weather conditions and instrument deviations. As one participant put it, “It could occupy valuable mental capacity”. Another major concern was over-reliance on technology, which most participants feared could lead to complacency and weaken a pilot’s ability to make quick, independent decisions in high-pressure situations. Separately, some highlighted technical limitations, noting that glitches, slow response speeds, or loading delays in AR overlays could be problematic during critical maneuvers, raising concerns about its practicality in real flight. Given these challenges, participants viewed AR as most effective in controlled settings, such as simulator-based learning, rather than in actual flight operations. They considered it particularly beneficial in the first 0–20 hours of flight training, when student pilots are still becoming familiar with cockpit layout, flight procedures, and basic aircraft handling. However, they emphasized that AR training should complement, not replace, real-world flight experience, as hands-on practice, in-flight decision-making, and instructor feedback remain irreplaceable in a pilot’s development. Furthermore, recognizing AR’s technological limitations, many participants preferred retaining a reliable, low-tech backup—such as standard checklists—for in-flight use. They suggested that as student pilots transition to flying solo, having a non-digital fallback would help reinforce decision-making and situational awareness, ensuring they can operate confidently without technological dependence. As one participant noted, “Checklists can be a reliable backup in any situation”. Participants agreed that when thoughtfully integrated, AR has the potential to serve as a valuable learning tool for skill development, offering structured reinforcement in the early stages while helping student pilots build confidence and proficiency without

diminishing their ability to operate independently in real-world flying conditions. As one participant summarized, “AR could help make early training more effective”.

Potential Use Cases for AR

Participants consistently highlighted the challenges of transitioning from ground school theory to actual flight exercises. Many traditional training methods, such as paper-based checklists and verbal instructor guidance, assume prior knowledge, making it difficult for beginners to apply concepts effectively. Participants noted that during early training exercises—such as familiarization, aircraft preparation, ancillary controls, and taxiing—student pilots have limited hands-on opportunities. As one participant observed, “It’s easy to miss details, making it challenging to keep pace with training and fully absorb them before applying them in practice”. As a result, when student pilots begin dual instruction in flight training, they could struggle with locating instruments, adjusting settings, and executing checklists, leading to hesitation and slower progress. Some participants also pointed out that this adjustment period could extend training timelines, requiring additional flight hours to reach proficiency. This, in turn, leads to higher training costs and scheduling difficulties, especially when aircraft and instructor availability may be limited. Participants believe AR-based training could provide structured reinforcement, allowing student pilots to engage with fundamental basics interactively in a risk-free environment, such as simulators, ultimately leading to a smoother transition to hands-on flight exercises.

Participants highlighted the challenge of developing procedural memory, particularly in executing structured flows from memory during routine flying operations. They noted that traditional training methods—cockpit posters, manuals, and verbal instruction—often fail to prepare student pilots for real-world execution. As one participant explained, “We’re given posters and diagrams to study these flows, but there’s not much muscle memory involved”. Many suggested that AR training in a simulated cockpit could bridge this gap by providing interactive visual overlays that can guide student pilots through each step in a structured sequence. As one participant said, “It’s easy to get lost in the flow of what comes next, but AR providing dynamic visual cues could help reinforce the sequence”. This approach, they believed, would help reinforce procedural flows, strengthen muscle memory, and instill accurate practices from the start.

Participants emphasized that early-stage flight exercises, such as attitudes and movements, straight and level flight, climbs, descents, and turns, form the building blocks of flight training. However, these exercises require student pilots to divide their attention across multiple tasks—aircraft control, instrument monitoring, and processing instructor feedback—all of which can be overwhelming and could lead to delayed corrections or unnoticed deviations. One participant remarked, “I imagine it’s a lot to keep track of at once, and small mistakes could add up quickly”. Many participants were concerned that difficulty in mastering fundamental exercises could not only extend training hours and increase costs but also create a

cascading effect, making subsequent training, such as circuits and landings, more challenging. They suggested that AR training could provide structured, step-by-step reinforcement in a simulated cockpit environment, helping student pilots transition more smoothly from foundational exercises to more advanced maneuvers with greater confidence. They saw AR as a potential solution for improving situational awareness and real-time decision-making, which can allow student pilots to visualize the correct actions in real time. Additionally, participants noted that traditional learning materials, such as checklists and cockpit posters, require frequent attention shifts, which can be distracting. They felt AR could mitigate this by keeping instructions within the student's direct field of view, helping them maintain focus and reducing cognitive load. As one participant explained, "With AR, I wouldn't have to keep looking down at a checklist and then back up. It keeps my focus where it needs to be". Participants also shared their frustration with training delays due to weather, aircraft availability, or scheduling conflicts, which often result in knowledge decay and force them to re-learn concepts before progressing. Many noted that when lessons get pushed out, student pilots may need to spend additional time revisiting previous material instead of progressing to new learnings, ultimately delaying advancement and increasing training costs. One participant remarked, "You forget a lot when you go a week or two without flying". To address this, some suggested using AR training in a simulated setting to reinforce knowledge during gaps in dual instruction training—not just for foundational flight exercises but also as student pilots advance through takeoffs, landings, circuit training, and more complex maneuvers. They anticipated this could help student pilots retain information between lessons, reducing the need for extensive review and enabling faster progression.

Another area where participants saw significant value in AR was emergency training, participants felt that memorizing emergency procedures without frequent real-world practice could be difficult. One noted, "I imagine in an actual emergency, it would be hard to recall everything under pressure if you haven't practiced it enough". Some questioned whether traditional methods, such as cockpit posters and written checklists, will be sufficient for building instinctive responses. They saw AR as a reinforcement tool in simulator-based training, where it could train student pilots through scenario-based drills while reinforcing proper response sequences. As one participant reasoned, "Practicing with a cockpit poster is static; you don't get tactile feedback. But in a simulator with AR, you can interact with the environment and reinforce emergency responses".

However, participants emphasized that AR-assisted learning should progress from guided instruction to independent execution as a structured approach to reinforcing learning and reducing reliance on visual cues. They recommended a tiered learning approach where AR lessons can initially be structured to provide step-by-step guidance but gradually shift to a validation mode, requiring student pilots to recall steps with minimal prompting. One participant summarized, "At first, AR could highlight everything for you, but later

it should wait to see if you remember before revealing the next step”. Participants also highlighted the importance of customizability, suggesting different training modes based on experience level. They noted that by gradually increasing the cognitive challenge, AR can potentially improve retention, enhance decision-making skills, and minimize hesitation under pressure, ultimately leading to more confidence in student pilots. Finally, participants recognized AR’s potential to accommodate different learning styles, pointing out that some student pilots learn best through visual guidance, others through auditory cues, and some by performing tasks hands-on. They believe AR’s multimodal approach could cater to diverse student needs, making training more personalized.

Considerations for Usability, Integration, and Adoption

For AR to be effectively integrated into flight training, participants identified several key challenges related to usability, system reliability, and adoption feasibility that need to be addressed to ensure its practicality and effectiveness. One major concern was the size and comfort of AR headsets, particularly for extended training sessions. While some participants found the weight manageable, others suggested that a lighter, glasses-style design would improve long-term usability. Additionally, interacting with AR through manual gestures or clicking mechanisms was seen as cumbersome in a high-paced training environment, potentially interrupting focus. Participants recommended incorporating voice commands or eye-tracking technology to make interaction more seamless and intuitive, reducing distractions during training. Another usability issue was the time required to set up AR equipment. Depending on the system, calibration, software initialization, and device synchronization may be needed before each training session, adding to delays. Participants noted that lengthy setup processes could cut into valuable training hours, making AR less efficient if it is not quick and easy to integrate into training workflows. As one participant pointed out, “If students are paying for training time, every minute spent setting up AR is money lost”. A plug-and-play solution was suggested as an ideal approach, allowing instructors and student pilots to transition smoothly into training sessions without unnecessary delays. Beyond usability, system reliability and performance were also key concerns. Some participants found that the response speed and loading time of AR overlays were a bit slow. They suggested that for AR training to be truly effective, it must maintain seamless performance and real-time responsiveness, as any unreliability or lag could hinder rather than enhance training effectiveness. As one participant put it, “If AR can’t keep up in real-time, it would end up being more of a distraction”. They recommended prioritizing system stability and speed to ensure that AR delivers timely and accurate information, making it a reliable tool for pilot training. Participants also emphasized that for AR to be widely adopted, it must be affordable and seamlessly integrated into pilot training programs without significantly increasing student costs. If AR technology adds financial strain, it may limit its practicality for both student pilots and training institutions. Accessibility was another key factor, with

participants highlighting the need for AR to be easily implementable in existing training environments without requiring extensive infrastructure upgrades or specialized equipment. As one participant pointed out, “If only the big flight schools can afford it, then it’s not really a solution for everyone”.

6.5 Discussion

6.5.1 AR-Assisted Pilot Training: Benefits, Challenges, and Future Considerations

This study found that AR training significantly reduced cognitive workload among ab initio student pilots, who are required to process large volumes of information while balancing theoretical knowledge with hands-on practice. By offloading cognitive effort, AR helps mitigate the challenges associated with traditional training methods, such as paper-based manuals, checklists and static cockpit posters, which rely heavily on memory recall and can create barriers to skill acquisition. AR alleviates this burden by allowing student pilots to focus more on task execution, improving procedural accuracy, and bridging the gap between abstract instruction and hands-on execution. However, while AR reduces initial cognitive load, its impact on long-term knowledge retention appears limited. The findings indicate that although AR’s guided learning approach enhances short-term performance by structuring procedural training around real-time instructional cues, it may also discourage active cognitive engagement, leading to weaker procedural internalization. The reliance on visual overlays may have led participants to execute tasks passively rather than actively constructing mental models, possibly explaining why AR-trained participants did not outperform those using traditional paper-based method in the retention exercise. To counteract this limitation, AR designs could incorporate phased learning, gradually reducing instructional support to encourage active recall and independent problem-solving while preserving the benefits of real-time AR guidance, ensuring student pilots develop self-reliant procedural knowledge without over-reliance on augmented cues.

Beyond cognitive workload, AR training also improved situational awareness, likely due to its ability to present information spatially, eliminating the need to interpret static materials. However, this study specifically focused on pre-flight inspection, a structured, checklist-driven task. Unlike dynamic flight scenarios, where situational awareness requires continuous monitoring and adaptive decision-making, pre-flight inspection follows a sequential, procedural process. Expanding AR to dynamic flight tasks, such as takeoff, approach, and emergency maneuvers, requires further exploration, as they would involve actively monitoring aircraft performance, airspace conditions, and other critical flight variables while maintaining an uninterrupted mental model. If AR overlays compete for visual attention, they may hinder rather than enhance situational awareness. To assess AR’s effectiveness beyond checklist-oriented tasks, future AR designs could explore adaptive systems that respond dynamically to changing flight conditions. Rather than

persistent visual overlays, AR design could incorporate context-sensitive, event-triggered prompts—activating only when critical conditions arise, such as reaching a designated altitude or entering a decision-making phase during approach. This selective delivery could potentially enhance situational awareness without overwhelming visual attention. Additionally, integrating multimodal feedback could further reduce reliance on visual overlays. Spatial audio cues could direct attention to critical instruments or warnings without requiring visual shifts, while haptic feedback on control surfaces could reinforce correct inputs in real time. These non-intrusive guidance mechanisms could help student pilots maintain situational awareness without compromising their ability to scan the operational environment. Furthermore, while AR overlays aid structured training, prolonged reliance may hinder scanning and prioritization skills in dynamic flight scenarios. Building on the previously discussed phased learning approach, AR cues for situational awareness tasks—such as altitude callouts, airspeed monitoring, and traffic proximity alerts—should gradually fade, encouraging student pilots to shift focus toward external scanning and cognitive prioritization. For example, during approach training, AR guidance could initially highlight glide path adjustments, but as pilots gain competency, these prompts could diminish, reinforcing self-reliant situational awareness.

One of the most promising findings of this study is that AR training significantly reduces instructor-provided assistance, supporting more autonomous learning. Given ongoing flight instructor shortages [1,366–369], AR could optimize training efficiency by allowing greater flexibility in scheduling and resource allocation, particularly in GA training programs. However, while AR reinforces procedural knowledge, it should complement not replace instructor-led in-flight training, as mentorship, adaptive decision-making, and real-world experience remain indispensable. This study highlights AR’s greatest value in early-stage training, particularly in ground school instruction and foundational flight exercises, where structured repetition and reinforcement are fundamental for procedural memory development. To ensure AR’s benefits do not compromise instructional quality, hybrid training models could be explored to accelerate skill development while keeping instructor mentorship central to refining judgment and adaptability. Additionally, AR can help mitigate knowledge decay caused by training gaps due to weather delays, aircraft unavailability, or scheduling conflicts, which often require students to relearn material before progressing. Findings suggest that AR-based procedural training could help maintain knowledge retention between dual instruction flight lessons, minimizing redundant review sessions and enabling more efficient skill development.

While AR was highly rated for perceived usefulness and ease of use, several practical challenges were identified, including visual obstructions, hardware comfort, and system lag. Participants reported that AR overlays interfered with their field of view, and the headset’s limited peripheral vision raised concerns about

its feasibility for in-flight use. Additionally, participants reported potential for discomfort during prolonged use, emphasizing the need for lightweight, ergonomic headset designs. System responsiveness was another concern, as AR overlays exhibited slight lag, affecting the seamlessness of training experience. Unless these challenges are fully addressed, the AR setup used in this study is better suited for controlled environments, such as classroom-based or simulator training, rather than direct in-flight applications. Notably, the study found no significant difference in simulator sickness symptoms between AR and traditional paper-based training, suggesting that AR does not inherently introduce additional discomfort. While these findings are encouraging for AR's usability, future research could explore longer-duration AR exposure to assess whether prolonged use may lead to any discomfort symptoms over time.

Despite AR's potential, its adoption in GA training could be hindered by financial and logistical constraints. Major airline training programs typically have greater financial flexibility to invest in advanced technologies, such as high-end simulators and immersive training systems, whereas smaller flight schools may face challenges with the high upfront costs of AR integration. To improve accessibility, future research could explore cost-effective AR solutions with minimal setup and seamless integration into existing training workflows. Future work could also examine alternative AR delivery methods, such as mobile-based or tablet-assisted AR, to further reduce hardware dependencies and enhance feasibility across diverse training environments. Regulatory acceptance will also be critical. AR will need to be evaluated and approved by aviation authorities as a recognized training method, with clear guidelines for its integration into certified training programs, defined performance benchmarks, and alignment with industry safety and competency standards.

6.5.2 Comparison with the Literature Reviewed

This study's findings align with prior research on AR's effectiveness in pilot training, particularly in enhancing situational awareness and reducing cognitive workload [23,25,278,283]. The structured and interactive nature of AR overlays helped student pilots process training tasks more intuitively, a benefit observed in both commercial and military flight training contexts [21,23,285]. However, this study differs from previous research in several key aspects.

While prior studies on AR in pilot training have primarily focused on commercial and military contexts, this research validates its impact specifically within GA training for ab initio student pilots, providing insights into its effectiveness in a real-world flight training environment. Unlike prior studies suggesting that AR enhances knowledge retention [278,288], this study found no significant advantage over paper-based training. A possible reason for this discrepancy is the difference in training environments. Earlier studies were conducted in simulator-based or classroom settings, where controlled conditions minimized external variability. In contrast, this study took place with an actual aircraft, where real-world factors—

such as environmental distractions, physical aircraft interaction, and cognitive load variations—may have influenced retention outcomes. These findings suggest that while AR can aid learning in structured environments, its benefits in unstructured, real-world settings require further investigation. Another key distinction is the focus on AR's usability challenges specifically within the GA training context. While existing literature highlights AR's performance benefits, fewer studies examine its practical application during real-flight operations. This study addresses that gap by incorporating pilot perceptions of AR's in-flight usability. Participants found AR to be beneficial for structured training tasks but raised concerns about its use during actual flight, citing visual obstructions, cognitive distractions, and potential over-reliance on augmented cues. While such concerns have been briefly acknowledged in operational settings, they have largely been explored at a surface level, with limited investigation into their implications for early-stage pilot training [25,284]. The findings of this study emphasize the need for AR tools to be carefully designed to support real-world flight operations effectively, ensuring they complement rather than interfere with pilot performance and situational awareness. Beyond usability concerns, this study also provides new insights into AR's impact on instructor dependence. Findings indicate that AR-trained participants required significantly less instructor intervention, supporting a shift toward more self-directed learning. While prior research has examined AR's role in reducing workload and improving procedural accuracy, its influence on training autonomy and instructor reliance has received little attention. The findings of this study suggest that AR could play a strategic role in mitigating instructor shortages in GA training programs [1,366–369], an issue that has not been widely discussed in the literature. Additionally, this study is one of the few to assess AR's physiological effects in pilot training. Using SSQ assessment, the results showed no significant difference in simulator sickness symptoms between AR and traditional paper training. This contrasts with concerns about motion sickness in immersive technologies, suggesting that AR, when properly implemented, may not inherently introduce additional discomfort for student pilots.

By focusing on GA training for ab initio student pilots, this study provides new insights that distinguish it from prior AR research in pilot training. Through training conducted with an actual aircraft, addressing in-flight usability concerns, analyzing instructor dependence, and incorporating sickness assessments, it offers a more comprehensive understanding of AR's applicability in early-stage pilot training. These findings highlight both the advantages and limitations of AR in this context, reinforcing the need for further refinement, adaptive instructional strategies, and a balanced integration of AR into existing training frameworks.

6.5.3 Implications for Pilot Training

The findings of this study highlight several key implications for pilot training, particularly in GA, where cost, accessibility, and training efficiency are often regarded as important considerations. One of the biggest

challenges for ab-initio student pilots is transitioning from theoretical instruction to practical execution, often requiring repetitive instructor demonstrations. AR can bridge this gap by complementing ground school instruction with self-directed, interactive modules, providing comprehensive exposure to foundational ground training exercises, including familiarization, aircraft preparation, ancillary controls, and taxiing, in a structured, hands-on environment before live operations. This can enhance in-flight training efficiency, reduce dependency on instructor-led demonstrations, and may help lower overall training costs. The significant reduction in instructor-provided assistance highlights AR's potential to support independent learning, strengthen procedural accuracy, and alleviate instructor workload, which is particularly beneficial given ongoing flight instructor shortages [1,366–369]. Leveraging this capability, AR can function as a structured procedural reinforcement tool, enabling student pilots to practice both fundamental flight exercises—such as attitudes and movements, straight-and-level flight, climbs, and descents—as well as more advanced flight operations like takeoffs, circuits, and landings within controlled training settings. By enabling guided independent practice, AR can help student pilots build confidence while maximizing in-flight training efficiency and reducing overall training costs by minimizing the need for repeated instructor-led sessions and optimizing aircraft utilization. Additionally, flight training is often disrupted by weather delays, aircraft unavailability, or scheduling conflicts, leading to knowledge decay between dual instruction flight lessons. AR can serve as a continuity tool, enabling students to review learnings, reinforce skills, and maintain training progression even when aircraft access is limited. Furthermore, AR's multimodal capabilities can cater to diverse learning styles—visual learners can benefit from interactive instructions, auditory learners from voice-guided instructions, and kinesthetic learners from physical cockpit interactions—ensuring a more personalized and engaging training experience. AR system equipped with real-time performance analytics can further optimize training by identifying individual skill gaps and dynamically adjusting instructional support, promoting targeted practice and adaptive feedback. Overall, given the high costs associated with instructor-led in-flight training, AR-based learning tools can offer a scalable and cost-effective supplemental training aid for foundational ground and in-flight training. If implemented effectively, AR has the potential to reduce the number of flight hours required for proficiency, leading to cost savings for both flight schools and student pilots. More broadly, these potential applications highlight AR's transformative role in pilot education, not only complementing traditional training methods but also addressing inefficiencies in accessibility, cost, and training continuity.

6.6 Limitations

This study included only 20 GA student pilots from a single aviation training institution, limiting generalizability. Variations in training methodologies, instructor approaches, and institutional resources

across different flight schools and regions may influence outcomes. Future research should incorporate a more diverse sample from multiple institutions to better assess AR-based training effectiveness.

This study evaluated AR's effectiveness only in pre-flight inspection procedure. While pre-flight inspection is a critical component of pilot training, the findings may not be directly applicable to other key training areas, such as in-flight decision-making, emergency management, and air traffic communication. Future research could explore how AR-supported instruction performs across diverse flight procedures, and training phases to further validate and extend these findings.

Retention in this study was assessed within a short period following training, limiting insight into AR's long-term effectiveness in knowledge retention. A longitudinal study assessing performance over weeks or months post-training would provide a clearer understanding of how well AR-trained skills are retained over time.

The study utilized the Microsoft HoloLens 2 as the AR platform, and findings may not be directly transferable to other AR devices with different hardware specifications, field-of-view limitations, or interaction modalities. Future research should explore AR-based training across multiple hardware platforms to evaluate consistency in user experience and training outcomes.

The study was conducted indoors within a hangar due to sunlight glare, which impaired AR visibility on the Microsoft HoloLens 2. The reflective nature of the display made it difficult for participants to see overlays clearly in direct sunlight, necessitating an indoor testing environment. These lighting constraints may limit the generalizability of findings to outdoor flight settings, where variable conditions could impact AR usability. Future research should assess AR performance in real-world outdoor flight environments under varying sunlight intensities, explore display optimizations to enhance visibility in bright conditions, and evaluate alternative AR hardware with improved adaptability to natural lighting.

6.7 Conclusion

This study highlights AR-assisted training as a promising supplement to traditional instructor-led pilot training, particularly for early-stage instruction in structured environments. By reducing cognitive workload, enhancing situational awareness, and supporting independent learning, AR can optimize instructor time, reinforce procedural accuracy, and improve training efficiency. However, seamless integration into broader pilot training programs requires addressing usability challenges such as visual obstructions, system responsiveness, and hardware ergonomics, while long-term retention remains an area for further study. Future research could explore AR's applicability in dynamic flight tasks, assess cost-effective implementation models, and incorporate instructor perspectives to ensure effective adoption.

While AR cannot replace hands-on flight experience and instructor mentorship, it has the potential to serve as a valuable reinforcement tool that enhances training accessibility, efficiency, and sustainability.

Chapter 7 (Study 6)

Augmented Reality Integration in Ab Initio General Aviation Pilot Training: Insights from Interviews with Certified Flight Instructors

7.1 Introduction

Ab initio pilot training—from the beginning, with no flight experience—has remained largely unchanged in general aviation (GA) for decades. Grounded in a traditional structure, it typically combines classroom-based ground school with one-on-one practical training delivered by a Certified Flight Instructor (CFI), the primary educator responsible for equipping student pilots with the knowledge and skills needed to operate aircraft safely. While this approach has long served the training industry, it is being scrutinized for its adaptability, slow integration of technological advancements, and questionable long-term sustainability.

Most current training programs follow a rigid, ‘one-size-fits-all’ framework that may not accommodate the diverse learning needs of student pilots [2,370,371]. This is particularly true for older student pilots — especially those over 40—who may experience age-related declines in cognitive flexibility, and processing speed. These student pilots often require more time to absorb complex procedures and can benefit from multi-sensory instructional strategies that reinforce understanding and decision-making. Instruction within the cockpit adds another layer of complexity [372,373]. Flying an aircraft is complex and cognitively demanding, and for ab initio pilots, the in-flight setting can be overwhelming—fast-paced, high-pressure, and saturated with information. In such conditions, student pilots are often so focused on controlling the aircraft that they struggle to absorb instruction in real time. Simultaneously, CFIs must divide their attention between assessing student performance and maintaining overall flight safety, limiting their ability to provide timely, in-the-moment feedback. As a result, valuable learning opportunities—so-called ‘teaching moments’—are frequently missed. Instruction is often deferred until after landing, when its relevance may have faded, or worse, the opportunity for learning may be lost entirely. Communication barriers can further complicate instruction, especially when cultural or language differences exist between CFIs and student pilots [374]. These barriers may lead to misunderstandings, miscommunication, and cognitive fatigue—particularly for ab initio pilots who are still developing foundational skills. Beyond instructional concerns, the flight training industry is facing growing systemic pressures [1,3,371,374–378]. Global demand for pilots continues to rise, driven by expanding aviation fleets and widespread retirements. This demand is further strained by a persistent shortage of CFIs, as many in GA use the role as a stepping stone to airline careers. High turnover reduces the availability of experienced CFIs, weakening training continuity and slowing the overall pipeline. Combined with high training costs, these issues contribute to an impending

pilot shortage. Meeting this challenge calls for training solutions that are not only more efficient, scalable, and cost-effective, but also focused on developing practical, hands-on competence. Adding to these pressures are growing concerns around environmental sustainability [3,379–381]. Traditional training methods, heavily reliant on in-aircraft instruction, contribute significantly to fuel consumption and carbon emissions. As the aviation industry navigates growing scrutiny over its environmental footprint, the demand for lower-impact training alternatives is becoming increasingly evident.

Amid these challenges, a timely opportunity has emerged to advance instructional methods that go beyond the capabilities of traditional training. Among the array of emerging educational technologies, Augmented Reality (AR) holds significant promise [382–385]. By enabling real-time interaction with digital content overlaid onto the physical environment, AR has the potential to deliver immersive, context-rich learning experiences. Its ability to boost engagement and support skill development has been demonstrated across diverse sectors, including healthcare, manufacturing, defense, and education. However, despite this potential, the integration of AR into GA training has made limited progress.

This study explores the perspectives of Certified Flight Instructors on the integration of Augmented Reality (AR), delivered through a wearable Head-Mounted Display (HMD), into ab initio pilot training as an assistive instructional technology. The focus is specifically on training within GA under the civil aviation sector. By examining instructor insights, this research aims to uncover both the opportunities and challenges associated with implementation, contributing to ongoing efforts to modernize pilot training in response to increasing demands for efficiency, inclusivity, and sustainability in aviation.

7.2 Literature Review

This literature review explores the potential of Augmented Reality (AR) to enhance ab initio pilot training for Private Pilot Licence (PPL) candidates in GA. It synthesizes findings from both experimental and non-experimental research, drawing on peer-reviewed studies and conference proceedings that evaluate AR's educational benefits and limitations using objective and subjective measures in operationally relevant contexts.

Several studies have investigated the utility of AR in enhancing classroom-based learning. Meister et al. explored the use of smartphone-based AR to supplement classroom instruction on thunderstorm dynamics [288]. Compared to traditional 2D print materials, the integration of interactive 3D visualizations led 6 participants—primarily student pilots and meteorology experts—to report enhanced theoretical comprehension, reduced perceived workload (NASA-TLX), improved usability (SUS), and positive learning outcomes. Similarly, Kim et al. developed an AR authoring tool aimed at enabling flight instructors to create AR content for aviation weather training without the need for programming expertise [289].

Compared to instructors' initial concerns and confidence levels, post-study findings from 41 participants—including both flight instructors and pilots—showed significantly increased confidence in creating interactive AR content, along with decreased concerns about technical complexity, mental effort, and time demands, suggesting strong feasibility for instructor-led AR content creation in ground school settings. Further supporting the role of AR in early knowledge acquisition, Northrup et al. introduced a mobile AR app designed to reinforce ATC communication and checklist training [287]. Feedback from ab initio student pilots—though the sample size was not specified—indicated improved comprehension, better engagement, and enhanced communication accuracy, highlighting the value of contextual and interactive AR experiences in replacing rote memorization. Fuchter et al. also explored procedural training using a life-size virtual flight panel delivered through a mobile AR app [286]. Although the sample size was not specified and no direct comparison group was used, ab initio student pilots reported gains in procedural memory, spatial awareness, and engagement when using the AR app—suggesting that such tools may offer instructional advantages over traditional checklist training methods in supporting pre-flight readiness.

AR has also shown promise in enhancing procedural training in simulated environments. Schaffernak et al. conducted two pre-test–post-test studies with novice student pilots ($n=3$; $n=14$) comparing traditional simulator training with HMD-based AR-supported instruction during landing practice [280,282]. The AR interface overlaid key flight cues—such as a flight path vector, airspeed, altitude, and a visual landing target—within the simulator environment. Compared to the control group, AR participants reported reduced workload (NASA-TLX), improved situational awareness (SART), decreased negative affect (PANAS), and higher training confidence (QCM), suggesting a more immersive and emotionally supportive learning experience. Moesl et al. investigated the use of AR for training VFR traffic procedures, including collision avoidance and visual scanning [386]. Among 59 flight-inexperienced students, those trained with AR showed significantly better scanning accuracy than those in simulator-only conditions. Subjective measures (NASA-TLX, SART, PANAS, QCM, ARI) indicated lower mental workload, higher engagement, and more positive emotions—underscoring AR's potential as a ground-based training aid for developing perceptual and attentional skills required for VFR navigation.

In addition to experimental research, only a limited number of studies have examined broader pilot perceptions of AR's role in training. Schaffernak et al. surveyed 60 pilots to explore potential AR applications in early-stage aviation education [348]. Participants identified key opportunities in classroom instruction, pre-flight inspection, and flight training, emphasizing AR's value in supporting learner-centered instructional design. Rizvi et al. extended this understanding by surveying 167 general aviation pilots after showing them video demonstrations of HMD-based AR flight training [2]. Approximately 80% of respondents expressed that AR could enhance pilot learning, particularly through immersive, self-paced

experiences that could support situational awareness without in-flight risks. Qualitative feedback also highlighted the perceived value of AR in improving safety and accessibility for novice pilots.

Although AR has shown promise across various areas of aviation training, relatively few studies have examined its potential within the context of ab initio training in GA, leaving significant gaps in the literature. Most studies focus on isolated ground school topics or specific flight phases—such as weather instruction or specific segments of the landing approach procedure—without addressing AR’s role across complete procedural workflows. Additionally, many rely on low-fidelity simulations, outdated hardware, or static AR cues, limiting the immersive and interactive potential of modern AR systems. A further limitation is the predominant focus on pilots and student pilots as participants, with limited attention given to CFIs. Although some research considered instructor perspectives, this line of inquiry remains sparse, leaving important questions about instructional integration, pedagogical value, and real-world feasibility unanswered. Many studies also suffer from small or unspecified sample sizes, reducing the generalizability of their findings. Moreover, the practical challenges of scaling AR tools for use in resource-constrained GA flight schools have received limited attention. To fill these gaps, the present study explores CFIs’ perspectives on integrating modern HMD-based AR technology into ab initio GA training. Uniquely, it incorporates a real-aircraft setting to provide a comprehensive, practice-informed understanding of AR’s instructional value and its potential for meaningful adoption in early-stage pilot education.

7.3 Method

7.3.1 Study Setting and Equipment

This study was conducted at the Waterloo Wellington Flight Centre (WWFC) based in Ontario, Canada. A Piper PA-28R-201 Arrow and a Cessna 172—both commonly used aircraft in GA pilot training [387]—served as the real-world training environment for the AR-based instructional experience, with a single aircraft used per session depending on availability. The Microsoft HoloLens 2 was used as the HMD to deliver the AR content. This mixed reality headset features see-through 1440×936 resolution lenses and a 52° field of view, along with spatial mapping, eye and hand tracking, gesture and voice recognition, and a flip-up visor that allows seamless transitions between digital overlays and the real world environment [294]. A custom AR application was developed using Unity and deployed on the HoloLens 2. Leveraging spatial mapping, the application anchored digital overlays directly onto the aircraft surface, ensuring accurate alignment between virtual content and physical components, and enabling interaction through air tap hand gestures. The application was configured to provide step-by-step instruction for the standard pre-flight inspection procedure—a structured walkaround conducted by pilots to ensure the aircraft is safe and ready for flight. The inspection sequence began in the cockpit and progressed around the tail, wings, and nose,

with visual overlays appearing in the HoloLens's field of view to highlight key components and provide inspection instructional cues that reinforced procedural accuracy and ensured proper inspection flow.

7.3.2 Participants

Eight CFIs were recruited from the WWFC through on-site advertising. All participants were actively involved in training student pilots enrolled in the PPL program. The sample included five males and three females, with an average age of 25.6 years and a mean total of 971.3 flying hours of experience ($SD = 343.5$). All participants held a valid Commercial Pilot Licence (CPL). Instructor ratings were distributed as follows: three held Class 4 rating, three held Class 3, and two held Class 2. None of the participants reported prior experience with AR technology, ensuring a uniform baseline for evaluating their interaction with the instructional setup. Participation was voluntary, and all CFIs received a fixed compensation for their time.

7.3.3 Procedure

Each CFI participated in a one-hour individual session that followed a standardized protocol to ensure consistency across participants. The session began with a 30-minute orientation, during which participants were provided with an information letter outlining the purpose of the study, data collection methods, and their rights as participants. They were given the opportunity to ask questions and were reminded of their ability to withdraw at any time before providing informed consent. All collected data were anonymized to maintain confidentiality. Following the briefing, participants completed a demographic and professional background questionnaire and then took part in a structured familiarization session with the AR instructional setup. This included hands-on training in basic AR interaction techniques (air tap gestures) and in developing spatial awareness for interpreting and engaging with virtual overlays in the physical environment, ensuring participants were comfortable using the setup before proceeding. In the final 30 minutes of the session, each participant engaged with the AR-enhanced pre-flight inspection lesson firsthand, using the actual aircraft. Although no student pilots were involved, participants were asked to complete the inspection lesson as if they were the intended student pilot, allowing them to evaluate the AR instructional setup from a student pilot's perspective. They followed step-by-step AR instructional overlays to complete the entire inspection procedure in the correct sequence. Figure 29 shows a study participant engaged in the AR-enhanced instructional experience of the pre-flight inspection procedure, while Figure 30 displays an AR instructional overlay in the participant's field of view, guiding the right-wing inspection. Upon completion, each participant took part in a semi-structured interview to discuss their impressions, highlight any usability challenges, and provide qualitative feedback on the instructional design and perceived value of the AR instructional experience. Interview questions are shown in Table 12.

This study was reviewed and approved by the University of Waterloo's Research Ethics Board (REB #46799). All procedures were carried out in full accordance with the board's ethical guidelines.



Figure 28. A study participant wearing the HoloLens while engaged in the AR-enhanced instructional experience of the pre-flight inspection procedure.



Figure 29 . AR instructional overlay shown in participant's field of view, assisting right-wing inspection.

Table 14. Interview questions using a semi-structured approach

1. What was the instructional experience like using the AR-based setup? <i>Follow-up: Did anything stand out to you—positively or negatively—about how the instruction was delivered?</i>
2. In what ways do you think AR-based instruction could support ab initio students during early stages of flight training? <i>Follow-up: Are there specific challenges that AR training might help overcome?</i>
3. Did you face or do you anticipate any usability issues with AR-based instruction? <i>Follow-up: What, if anything, would you change to improve usability?</i>
4. Do you believe integrating AR-based instruction into existing GA training programs is feasible? <i>Follow-up: What logistical, instructional, or operational considerations do you consider relevant?</i>

7.3.4 Data Analysis

Thematic analysis was conducted on insights obtained from the semi-structured interviews, following the methodology outlined by Braun et al. [319]. This approach facilitated the systematic identification of recurring patterns, themes, and perspectives within the data, thereby informing the study's findings.

7.4 Results

Two researchers independently analyzed the semi-structured interview responses using thematic analysis, applying both deductive and inductive coding approaches. Deductive coding was guided by established theoretical frameworks, organizing the data into predefined themes informed by prior literature. These included: Enhancing Theoretical Education Through AR-Enabled Learning [286–289], which focused on improving theoretical understanding and increasing learner engagement through interactive and visual experiences; AR-Supported Procedural Learning [280,282,286,386], which examined AR's integration into structured training environments to support standardized procedural instruction; and Pilot Perceptions of AR Integration [1,2,348], which explored how pilots perceive the broader utility of AR in training, particularly in terms of safety, accessibility, and learner-centered instructional design. In parallel, an inductive, data-driven approach was used to allow themes to emerge organically from participants' responses, uncovering insights beyond the scope of existing frameworks. The emergent themes included: Accessible Instructional Innovation, which highlighted AR's potential to improve early-stage pilot training through intuitive, instructor-friendly tools that could reduce technical and cognitive barriers; Self-Directed Procedural Mastery, which emphasized AR's role in supporting independent, self-paced development of procedural skills and situational awareness, particularly in contexts lacking real-time instructor feedback; and Challenges and Limitations, which addressed practical concerns related to AR implementation, including physical discomfort, ergonomic constraints, and usability issues during extended use.

Building on both deductive and inductive findings, four interrelated themes were identified: Usability, Operational Constraints, and Adoption Considerations, which explored concerns about AR's practicality in

real-flight environments, emphasizing challenges related to comfort, compatibility, and system reliability, while highlighting the need for ergonomic design, ease of use, and affordable implementation in controlled settings; Opportunities in Ground-Based Training, which highlighted AR's potential to reinforce foundational knowledge through structured, step-by-step guidance in ground-based environments, helping address early training gaps without replacing traditional instruction; Reinforcement Tool for Foundational Flight Instruction, which focused on AR's value as a self-paced, multi-sensory tool to support procedural memory and learning retention during early flight exercises, especially in simulators or home-based practice; and Supplementary Approaches to Strengthen Specialized Flight Instruction, which examined AR's role in helping student pilots refine complex maneuvers and emergency procedures to support readiness for solo flight. The findings under each theme are detailed below, reflecting only participant perspectives, with no additional analysis or interpretation by the authors.

Usability, Operational Constraints, and Adoption Considerations

Participants expressed skepticism about the practicality of using AR training solutions during actual flight operations. A central concern was the challenge of multitasking in an already high-stress, physically demanding cockpit environment. As several participants noted, pilots are already juggling complex procedures, situational awareness, and communication with air traffic control—tasks that require full concentration. Introducing an additional device, particularly one requiring visual focus or physical interaction, was seen as a potential distraction. As one participant summarized it candidly, “Flying in general is strenuous in the plane, so having another device adds another level of distraction”. For many, the cockpit of a flying aircraft—particularly during ab initio training—was seen as an unsuitable environment for attention-demanding technologies. Concerns also extended to the physical and logistical challenges of using AR headset in flight. Participants pointed out that most student pilots often wear both sunglasses and aviation headsets, which can complicate the use of additional head-mounted wearables. “You will have to take the aviation headset off to use this AR device”, one participant explained. The weight and bulk of AR headset were also described as uncomfortable—particularly in turbulent, high-temperature conditions that are common in flight. As one participant remarked, “Wearing something heavy on your head isn’t exactly ideal for training”, emphasizing that discomfort could diminish instructional focus and performance. Some participants suggested exploring lighter, more ergonomic headset designs that could be worn in combination with standard aviation headsets or integrated directly into them. Others pointed to emerging options such as transparent, see-through smart glasses. Beyond comfort, participants identified several usability and accessibility issues. The reliability of AR system was called into question due to sensitivity to calibration and alignment, sharing that even slight headset misalignment can render the experience ineffective. “If the headset’s orientation shifts during flight, it can cause noticeable drift in content

alignment”, one participant noted, raising consistency and safety concerns during in-flight use. Student pilot with vision impairments or who wear glasses were seen as especially vulnerable to these limitations. Gesture-based controls were also criticized for being clunky and potentially intrusive for in-flight training scenarios. Several participants suggested voice- or sound-activated inputs as more intuitive, hands-free alternatives that could reduce cognitive and physical workload.

While AR use during actual flights raised many red flags, participants were overwhelmingly supportive of its use in controlled training environments like simulators and ground-based rehearsal. These environments were viewed as safer, more forgiving, and better suited for immersive, procedural learning. However, even in simulator-based environments, several barriers remained.

Participants identified several important considerations for making AR training solution more effective, usable, and accessible. Extended headset use was flagged as uncomfortable—particularly for those with high-prescription glasses. This further underscored earlier suggestions for lightweight, ergonomically designed headsets and solutions that can accommodate prescription eyewear. Lengthy setup times were also seen as a deterrent, especially when they cut into scheduled training sessions. Participants widely recommended plug-and-play solutions that minimize setup effort and integrate seamlessly into existing training workflows. They also highlighted opportunities to enhance instructional delivery, emphasizing the importance of more effective visual presentation. One commonly suggested improvement was to replace plain text with visual media—such as icons, illustrations, or short videos—which were viewed as more intuitive and engaging, especially for student pilots who process information better through imagery. When spatially aligned with cockpit components like switches, levers, or instruments, such visuals were seen as highly beneficial for reinforcing procedural memory and providing immediate context. This was considered especially valuable for ab initio students, who often struggle to grasp cockpit layout and systems in early training. More broadly, participants emphasized that AR tools should offer design flexibility to support different learning styles, reduce reliance on text-heavy instruction, and promote clearer, more interactive guidance. By tailoring content to be more visual, accessible, and aligned with how student pilots learn, participants believed AR could meaningfully improve comprehension, retention, and confidence. Affordability was another major consideration. With flight training already being expensive, there was concern that AR implementation could add financial strain—particularly if costs are passed onto student pilots. “It needs to get to a point where everything’s cheap, and affordable enough to actually be worth it”, one participant noted. For AR training to scale effectively, participants stressed that both the AR authoring tools, and hardware must remain financially accessible. Several participants also brought up a systemic barrier: access to simulators themselves. Participants noted that in many pilot training programs, simulator time must be purchased separately—often at a significant portion of the cost of in-aircraft instruction. They

observed that this pricing structure discourages student pilots from taking full advantage of simulators, despite their instructional value. In contrast, some pointed to programs where simulator access is bundled or freely available, noting that students in those settings engage more consistently. Participants felt that such environments could be more conducive to leveraging the full potential of AR-based training solutions. At the same time, participants were careful to point out the limitations of simulation environments—regardless of AR integration. They emphasized that simulators cannot fully replicate real aircraft behavior. As one participant put it, “It’s called a simulator for a reason. If it did exactly what the airplane does, it would be called a duplicator”. Specific concerns were raised about the lack of realism in control input, throttle response, and flap behavior—areas where the simulated feedback often diverges from actual flight dynamics. For this reason, participants viewed AR training solution—when integrated into simulation environment—as a supplementary tool that can enhance competencies, rather than replace, traditional instructor-led flight instruction. They underscored that real-world flying experience, in-flight decision-making, and instructor-guided feedback remain fundamental to pilot development.

In addition to hardware and cost concerns, participants highlighted challenges with AR content creation, particularly a lack of technical expertise. Authoring tools that require scripting, 3D modeling, or navigating complex development environments were seen as intimidating and impractical. To address this, participants emphasized the need for simplified interfaces that align with their instructional workflows and mental models. Features such as drag-and-drop editing, intuitive scene setup, and real-time previews were viewed as empowering. The ability to embed quizzes, instructional prompts, and scenario-based guidance directly within the AR environment was also seen as key to maintaining pedagogical control. Ultimately, participants consistently emphasized that sustainable adoption of AR tools depends on ease of use, a short learning curve, and alignment with how instructors already teach. Intuitive design and minimal onboarding were seen as especially important, particularly for those without a technical background. As one participant put it, “It should fit into how we teach—not force us to teach differently”. Therefore, without these core elements, even the most advanced AR solution could risk being underutilized or go unused altogether.

Although participants were clear-eyed about current limitations—ranging from headset discomfort to systemic barriers—they remained optimistic about AR’s long-term potential. Many believed that, with the right enhancements and thoughtful implementation, AR could significantly enrich simulator-based training. As one instructor concluded, “The idea itself is great—it just needs to evolve”.

Opportunities in Ground-Based Training

Participants consistently shared concerns about inefficiencies in early-stage flight training, particularly during the first three foundational exercises of PPL training—Familiarization, Aircraft Familiarization and Preparation for Flight, and Ancillary Controls. They explained that while these exercises are intended to

help student pilots become comfortable with the cockpit layout and build confidence in using the aircraft's primary controls—such as the yoke, rudder pedals, and throttle—they often receive limited instructional focus. As a result, student pilots tend to spend a significant portion of their initial flight hours—sometimes between 5 to 15—just orienting themselves before formal dual instruction even begins. As one participant put it, “Some students spend the first several flight hours just getting a feel for the cockpit—familiarizing themselves with where everything is and how it all works—before they even begin the actual flight exercises”. This delay, they noted, pushes back the timeline to solo flight and can extend the overall duration of PPL training. Participants also described how the delivery of this early training varies depending on the setting. They noted that student pilots in smaller Flight Training Units (FTUs) often benefit from more hands-on, individualized instruction, whereas larger, program-based FTUs tend to rely on brief group orientations. While introductory flights were acknowledged as helpful, participants felt that without consistent, structured reinforcement, the information introduced in these sessions is rarely retained. This challenge, they added, is compounded by how little emphasis is placed on these foundational exercises during instructor development. Since these three exercises are not evaluated in the Class 4 instructor flight test, several participants felt they tend to be overlooked. They also noted that Class 1 instructors don't always stress the importance of these early exercises when mentoring new instructors, which further contributes to their neglect. As a result, many student pilots are left to pick up foundational knowledge informally—and inconsistently—once actual flight exercises begin. Several participants described this fragmented approach as a barrier to student progress, noting that it undermines training efficiency and slows student progress.

In response to these issues, participants pointed to AR as a promising way to close early-stage training gaps. They viewed AR as a tool that could support structured, step-by-step guidance in practical, ground-based settings—whether in a stationary aircraft, simulator, mock-up cockpit, or classroom with aircraft panels. Many felt that AR lessons covering early-stage training could help student pilots build confidence and familiarity with cockpit layout by offering interactive visual overlays to support tasks like completing pre-flight checklists and other cockpit preparation activities. One participant shared, “When a student looks at something like the fuel selector or magneto switch, the AR system could highlight it with labels or prompts to reinforce their proper usage and help students understand how the systems work”. They added that this kind of context-specific feedback could enable student pilots to move through early training at their own pace while strengthening their understanding of aircraft systems and control functions. Participants also emphasized the value of enabling student pilots to revisit foundational lessons independently—without being limited by instructor availability—and appreciated the potential for AR to promote greater consistency in how content is delivered. Still, many were clear in stating that AR lessons should not replace

ground school instruction. Rather, they saw it as a supplement, best used after an initial introduction to aircraft systems through classroom learning or one-on-one briefings.

Reinforcement Tool for Foundational Flight Instruction

Participants consistently highlighted the difficulty of determining whether student pilots are truly absorbing information during flight lessons. The cockpit environment—noisy, time-pressured, and cognitively demanding—was seen as limiting opportunities for real-time clarification or formative feedback. As one participant noted, “You are not even sure if the information that you are sharing is being fully absorbed.” This concern led many to view AR training as a promising supplement to traditional flight instruction—not as a replacement, but as a tool that could reinforce key learning through self-paced, experiential practice in controlled environments, such as simulators or structured home settings. This AR-supported learning was seen as especially valuable for strengthening procedural memory and accommodating different learning preferences through flexible, multi-sensory engagement (e.g., instruction delivered through visual, auditory, and interactive media). As one participant put it, “You know as well as I do too, some people learn differently”.

When used in simulator settings, AR’s ability to deliver step-by-step instruction in a clear and structured format was viewed as particularly useful to supplement early flight exercises—Attitudes and Movements, Straight and Level Flight, Climbing, Descending, and Turns—where gaps in understanding can result in persistent errors. Participants noted that student pilots often take 8 to 10 hours or more to gain proficiency in these foundational exercises and believed simulator-based AR training could accelerate skill development by offering consistent, targeted reinforcement. Participants proposed that future iterations of AR could function as a real-time co-instructor by incorporating feedback features. Even basic cues—such as confirming task completion, prompting retries, or offering corrections—were seen as helpful for enabling student pilots to recognize and address mistakes during self-guided practice, making the experience more interactive and effective. Weather-related cancellations were frequently cited as a barrier to learning continuity. Participants noted that extended gaps between flight lessons often resulted in noticeable skill decay. One estimated that student pilots may retain about 70% of a lesson within the first week, but that retention drops below 40% after just a couple of weeks without any review. While instructors typically revisit previous material at the start of each flight lesson, participants believe simulator-based AR training could provide a more consistent and engaging way to support retention during interruptions.

In addition to simulator use, participants reflected on AR’s potential to enhance home-based training. “Couch flying”—at-home mental rehearsal of procedures—is often encouraged to help student pilots build procedural familiarity outside the cockpit. This has typically involved static cockpit posters, which one participant described as “the traditional way”. Many participants felt that AR could offer a meaningful

upgrade to this approach. Participants described how projecting interactive overlays onto flat surfaces—such as desks or walls—could allow student pilots to mentally and physically engage with cockpit elements. This approach was seen as enabling more tactile and realistic walkthroughs of flows, checklists, and instrument layouts. Many viewed it as a dynamic and accessible way to reinforce procedural memory without requiring access to a simulator or aircraft.

Supplementary Approaches to Strengthen Specialized Flight Instruction

Participants identified several areas of flight training where student pilots frequently struggle and where simulator-based AR training could offer meaningful supplementary support to traditional flight instruction—particularly in complex maneuvers and emergency procedures. While these specialized procedures are typically introduced during dual instruction, participants noted that students are often expected to refine and perform them independently during solo flight. Given the absence of real-time guidance during solo flights, AR was viewed as a promising tool to bridge that gap—providing targeted reinforcement in a low-risk, simulator-based environment and supporting overall readiness to conduct solo flights.

When discussing flight exercises, participants often pointed to steep turns, stalls, and slow flight as especially challenging for ab initio student pilots. Steep turns, in particular, were described as difficult due to their visual and physical asymmetry between left and right, which complicates the development of muscle memory and situational awareness. Participants suggested that AR could overlay visual references to illustrate proper aircraft attitudes and angles, allowing student pilots to build accurate mental models through repeated exposure. One participant explained, “If you have that image already set and it is reinforced using AR assistance, it might take less time to try to improve that skill”. Another noted that student pilots sometimes hesitate to bank fully during steep turns, leading to inconsistent angles: “They are kind of afraid to turn all the way to 45 degrees and so it's not like a constant angle they are maintaining”. Beyond visualization, some participants suggested that AR lessons could also be setup to deliver cues—such as “watch airspeed” or “add more rudder”—to replicate an instructor’s in-the-moment corrections. This was seen as a way to promote self-monitoring and help students develop greater independence in identifying and correcting performance deviations. Participants noted that such functionality would be particularly feasible if the AR system were fully integrated with simulator telemetry, allowing it to track control inputs and aircraft behavior in real time. With access to live simulator data, AR could identify deviations from expected performance and deliver context-sensitive prompts to guide corrective action.

Building on these insights, participants identified emergency training as another area where simulator-based AR training could provide substantial support—particularly in helping student pilots internalize ‘memory items’, or critical procedures that must be carried out immediately during an emergency. While

checklists are technically accessible in flight, participants pointed out that the time pressure and stress of real emergencies could prevent student pilots from referencing them in the moment. As one participant explained, “On the ground we use checklists for pre-flight or taxi procedures, but in the air, it’s all memory items”. Others echoed that even when an emergency checklist is available onboard, the expectation in many scenarios is to perform certain ‘memory items’ before consulting a checklist. While participants acknowledged that simulators already allow for repeated practice, they felt that simulator-based AR training could add further value by enabling step-by-step, hands-on rehearsal enriched with layered visual and contextual instructional cues. This, they suggested, could help student pilots internalize procedures more effectively for high-pressure scenarios. Some participants discussed ways to use AR not just for instruction, but also to test and reinforce memory under pressure. Participants proposed structuring AR lessons to taper guidance over time or introduce delays, thereby challenging student pilots to strengthen recall and make decisions independently. As one participant described, “Start off by always highlighting the action, and then start to induce some sort of delay, like a test”. This approach, they felt, could help procedural responses become automatic. As another participant put it, “Then in the airplane, students are not trying to remember—they are just doing”. Many also reflected that hesitation and freeze responses are common during real emergencies, particularly among less experienced student pilots. One participant shared, “Once you actually get into a tricky situation, your brain starts shutting down.” They felt that repeated, immersive AR lessons on emergency procedures could help build the confidence and fluency needed to respond decisively.

7.5 Discussion

7.5.1 AR-Enhanced Instruction: Potential Opportunities, Challenges, and Implications

This study explored CFIs’ perspectives on integrating HMD-based AR technology into ab initio GA pilot training. The findings revealed cautious optimism, signaling that while AR is not seen as suitable for in-aircraft use—due to concerns about distraction, discomfort, and operational impracticality—it holds considerable promise in ground-based and simulator-supported training contexts. CFIs emphasized that AR should not replace traditional instruction but rather serve as a scaffold (assistive tool) to enhance self-paced learning, reinforce procedural memory, and simulate instructor presence in structured environments. These insights suggest a clear role for AR as a complementary instructional aid, especially for ab initio student pilots in early training phases. By enabling structured, step-by-step instruction and supporting multimodal learning, AR could help reduce cognitive load to facilitate deeper learning and improve retention—potential instructional advantages in the context of GA training, where training continuity can be frequently disrupted by weather conditions or scheduling constraints.

A central finding of this study was the consistent underemphasis on foundational ground-based training exercises—such as Familiarization, Aircraft Familiarization and Preparation for Flight, and Ancillary Controls—which are essential for building early competence but are often glossed over in current instructional practice. CFIs identified these gaps as both structural and pedagogical shortcomings within the PPL framework, noting that these early-phase exercises are insufficiently reinforced in instructor development programs and largely absent from their formal assessment criteria. This lack of emphasis creates variability in readiness of student pilot and can delay progress toward key milestones like solo flight. In this context, AR emerges as a timely and targeted instructional solution. By offering visual, step-by-step interactive walkthroughs, AR-assisted training can help standardize these foundational exercises and provide student pilots with opportunities to build familiarity and confidence at their own pace. This will not only support the development of a consistent baseline of competence across student pilots but may also reduce overall training inefficiencies, potentially accelerating training milestones. To translate this potential into practice, flight schools and curriculum developers could prioritize the integration of supplementary AR modules into foundational ground-based exercises to enhance instructional consistency and more effectively prepare student pilots for the initial stages of flight training.

Beyond foundational skills, CFIs also emphasized AR's value in strengthening procedural memory—especially for maneuvers and procedures that are difficult to practice extensively during real flight due to the time-pressured nature of flight lessons, where instructional priorities and tight scheduling could limit opportunities for repetition and focused skill development. AR-enhanced simulator lessons, when combined with contextual guidance and telemetry-based adaptive feedback, can act as a virtual co-instructor. They can support student pilots in rehearsing fundamental control movements—such as straight and level flight, climbs, descents, and coordinated turns—as well as specialized maneuvers like steep turns, stalls, and checklist-based procedures (e.g., pre-takeoff checks, engine start procedures, and before-landing checklists) during off-flight hours. The inclusion of metacognitive supports—such as alerts when parameters deviate—could promote self-monitoring and skill refinement. CFIs further recommended that AR guidance be gradually withdrawn to support memory consolidation and foster independent performance. This tapering could mirror scaffolding principles in instructional design and may increase long-term retention while supporting confident, consistent execution of trained maneuvers and procedures during flight.

Emergency procedures training was another area where CFIs particularly highlighted AR's instructional value. The ability to rehearse high-pressure, time-critical responses in a safe, repeatable format provides a unique opportunity to enhance both confidence and recall—two critical factors in emergency performance. This capability can be especially valuable in GA, where limited exposure to emergencies can undermine

preparedness. In this context, AR can provide an important instructional supplement by delivering structured, step-by-step reinforcement that supports guided learning, enabling repeated exposure to emergency scenarios in a controlled environment. Moreover, the progressive fading of guidance within AR lessons could mirror principles of deliberate practice and cognitive scaffolding, facilitating the transition from declarative to procedural knowledge. This tapering takes on greater significance for emergencies. It can enable student pilots to transition from checklist-based knowledge to instinctive action under stress, fostering the development of automaticity and muscle memory.

Given these findings, GA PPL training programs could explore integrating AR modules into ground school, pre-flight preparation, and as a means of providing consistent instructional reinforcement between flight lessons. These modules could be structured in alignment with the PPL syllabus to support progressive skill development and ensure relevance to existing training workflows. Furthermore, the design of AR content should reflect how student pilots acquire and retain complex procedural knowledge. Instructional designers and pilot training organizations will have to be encouraged to develop AR lessons grounded in evidence-based learning principles such as Cognitive Load Theory and Dual Coding Theory [388,389]. In this light, AR represents more than a technological enhancement—it is a pedagogical opportunity to strengthen training continuity, promote learner autonomy, and improve instructional consistency in a domain where access to standardized instruction is often constrained by limited training time, weather conditions, safety considerations, or restricted access to qualified instructors or training aircraft.

Despite this enthusiasm, CFIs cited several practical barriers that could hinder the effective adoption of AR in GA training. At the device level, concerns included ergonomic discomfort during extended use, incompatibility with standard aviation headsets and prescription eyewear, and technical issues such as lengthy setup times, which can reduce efficiency and may discourage frequent use during short training sessions. These challenges point to a need for aviation-specific design refinements in AR hardware—such as lightweight, headset-compatible form factors and simplified setup protocols—to better align with the operational realities of flight training environments. In addition to hardware concerns, many CFIs also pointed to the difficulty of authoring AR content without technical expertise. This underscores the need for accessible content creation tools—such as drag-and-drop editors, real-time previews, and plug-and-play functionality—that can reduce instructor workload and support customization.

Beyond device-specific issues, CFIs also raised broader systemic challenges—most notably, limited access to simulators and the high cost of AR hardware and software. Without an accessible ecosystem and adequate infrastructure for AR delivery, the financial and operational burden may fall disproportionately on student pilots. These concerns suggest that effective AR integration cannot be left to individual instructors or informal efforts by training organizations; instead, it will require coordinated support at the

institutional and regulatory levels to ensure equitable and sustainable adoption. Public-private partnerships, equipment subsidies, and shared access models (e.g., mobile AR kits or cloud-based training hubs) could help democratize access and reduce financial strain on student pilots. In parallel, regulatory recognition of AR-enhanced training—particularly for its role in addressing instructional gaps—could further incentivize adoption and standardization.

Collectively, these findings reinforce that realizing the full potential of AR in GA training will require a dual-pronged approach: technological refinement to ensure usability and reliability, and infrastructure-level investment to ensure equitable access and instructional alignment. Without addressing both dimensions, AR's utility may remain limited to isolated use cases rather than driving meaningful transformation across the broader training landscape.

7.5.2 Management and Economic Considerations

In addition to pedagogical and technical implications, this study also surfaces important management and economic considerations that may influence the integration of AR in GA training environments. Two persistent challenges in this context are the high turnover of CFIs and their low compensation structure that governs much of their work [1,377,390–392]. Because many CFIs treat their role as a temporary pathway to airline careers, instructional continuity is often compromised—student pilots may receive guidance from multiple CFIs with varying levels of experience, leading to inconsistency in how lessons are taught and reinforced. Separately, the prevailing compensation model—typically limited to classroom time or logged flight instruction while the aircraft engine is running—discourages investment in activities that fall outside paid hours, such as pre-flight walkarounds, checklist rehearsals, or one-on-one procedural coaching. These activities, while critical for developing early pilot competence, may be deprioritized due to financial disincentives.

In this context, AR presents a practical opportunity to buffer the instructional system against both CFI turnover and compensation-related instructional gaps. Immersive, self-paced AR modules could serve as a form of instructional continuity, ensuring that both foundational ground-based lessons and reinforcement for in-flight exercises are delivered consistently, regardless of an CFI's availability, experience, or turnover. By supporting standardized delivery across a range of training contexts, AR assisted training can help mitigate the variability introduced by rotating CFIs and offer student pilots greater stability throughout their learning trajectory. Additionally, AR can alleviate the burden on CFIs who may be disincentivized from covering unpaid or underpaid instructional segments, while still ensuring that student pilots receive critical guidance in both preparatory and in-flight phases of training. However, this instructional shift may also raise concerns among CFIs who rely on hourly compensation. Some may perceive AR as reducing their instructional value or cutting into potential earnings, particularly if it displaces time traditionally spent with

student pilots. Tensions may also arise between student pilots seeking cost-effective training and CFIs aiming to maximize paid hours. To address these challenges, careful change management will have to be required. Schools may need to reframe AR as a complement to CFI roles, introduce compensation models that recognize CFIs' roles in supervising or customizing AR content, and consider recognizing AR-assisted instruction as part of official training time.

Ultimately, the success of AR adoption will depend not only on its instructional and technical merits but also on how well it aligns with the economic realities of GA training. When thoughtfully integrated, AR could help reduce training variability, lower costs for student pilots, and relieve CFIs of repetitive, low-compensated tasks—offering a more sustainable and scalable training model for both schools and student pilots.

7.5.3 Comparison with Literature

This study aligns with prior research demonstrating the educational value of Augmented Reality (AR) in pilot training. Consistent with findings from Meister et al. and Northrup et al. [287,288], CFIs recognized AR's ability to enhance learner engagement and conceptual understanding through interactive visualization. Echoing Kim et al. [289], they emphasized the importance of instructor-led content creation but stressed the need for intuitive, low-barrier authoring tools, noting that technical complexity remains a key obstacle—particularly for instructors without programming expertise. CFIs also supported AR use in simulator and ground-based settings, consistent with findings from Schaffernak et al. and Moesl et al. [280,282,386]. These studies demonstrated AR's effectiveness in procedural learning and workload reduction—strengths that CFIs saw as especially valuable in low-risk, repeatable environments suited for early skill acquisition.

Beyond reinforcing existing insights, this study offers a valuable practice-based perspective from CFIs engaged in *ab initio* GA training—a group often underrepresented in AR research, which has primarily focused on the experiences of student pilots or licensed pilots. This perspective brings forward critical considerations about how AR can be realistically integrated into instructional practice and pedagogy, including instructional pacing and established curriculum structure. The study also addresses an overlooked area in the literature: the early stages of flight training. While most prior research has concentrated on isolated tasks such as checklist use or weather briefings, this study highlights AR's potential to support full procedural workflows, including ground based foundational lessons—areas that CFIs identified as essential yet inconsistently delivered. In addition, the study provides a grounded assessment of practical adoption barriers, including headset discomfort, gear incompatibility, setup complexity, limited simulator access, and cost. These insights underscore the need for broader institutional and regulatory support to ensure equitable and sustainable implementation. Importantly, the study positions AR not as a replacement for traditional instruction but as a complementary tool that must be aligned with current training systems and

responsive to systemic challenges such as instructor shortages, student variability, and weather-related delays. Finally, a unique contribution of this study is the identification of instructor-led concerns regarding the use of AR during ab initio flight training, specifically related to distraction and cognitive overload. These findings underscore the importance of defining AR's role as a ground-based supplement rather than an in-flight aid, particularly for preparatory and reinforcement learning.

7.6 Limitations and Future Research

This study should be interpreted with several limitations in mind, each of which offers an opportunity for future research. These have been outlined below.

This study evaluated AR's effectiveness only in the pre-flight inspection procedure. While this is a critical part of pilot training, the findings may not be directly applicable to other key areas such as in-flight decision-making, emergency management, or air traffic communication. Future research could examine AR's instructional value across a broader range of flight training tasks—including steep turns, forced landings, and emergency checklists—to assess its broader applicability and support for varying learning objectives.

The study focused exclusively on CFIs' perceptions, without incorporating student pilot perspectives or performance data. This limits insight into how student pilots could engage with and benefit from AR-based instruction. Future studies could include student pilot participants to evaluate how AR impacts learning progression, confidence, and cognitive workload, particularly among diverse age groups and nontraditional backgrounds.

Only eight CFIs from a single Canadian training center were involved, which may limit the generalizability of the results to other geographic regions, regulatory environments, or institutional contexts. Larger-scale, multi-site studies are needed to understand how AR integration could be influenced by local training cultures and infrastructure differences.

The study was based on a specific AR platform—the Microsoft HoloLens 2 paired with a custom-developed application. Findings may not hold across other AR systems that vary in cost, usability, and interaction design. Further research could compare different hardware platforms, including more affordable smart glasses or mobile-based AR solutions, to determine their viability for widespread use in resource-constrained FTUs.

Participants interacted with the AR system only during a single, controlled session, which doesn't capture sustained engagement or long-term integration into instructional workflows. Longitudinal research is needed to examine how AR use could evolve over time, including aspects like skill retention, training fatigue, and operational efficiency when used over multiple lessons.

This study also did not explore adaptive or intelligent AR feedback mechanisms. Future work could investigate dynamic AR systems that provide real-time, context-sensitive guidance—such as alerts for instruction deviations or incorrect inputs—based on student pilot actions or simulator telemetry. This could enable more personalized and effective instruction.

The study took place inside a hangar to mitigate the effects of sunlight glare, which reduced the visibility of AR content on the Microsoft HoloLens 2. The headset’s reflective display made it challenging for participants to view AR overlays clearly in direct sunlight, making an indoor setting necessary. These lighting-related limitations may affect the applicability of the results to outdoor aviation contexts, where changing light conditions could influence AR effectiveness. Future studies could examine how AR performs in outdoor flight environments under different lighting intensities, investigate ways to improve display visibility in bright settings, and consider alternative AR devices better suited to natural light exposure.

7.7 Conclusion

CFIs viewed AR as a valuable supplement for ground and simulator-based instruction, especially in the early stages of pilot training when procedural confidence, retention, and readiness are still developing. They emphasized its potential to reinforce key skills, standardize instruction, and sustain learning continuity during common disruptions such as weather delays or CFI turnover. If thoughtfully designed—with intuitive interfaces, lightweight hardware, and clear, modular content—AR is expected to hold strong potential to support self-paced, low-risk skill development and serve as a scaffold to complement traditional teaching. Effective integration, however, will depend on overcoming barriers such as hardware cost, limited simulator access, and content development complexity. CFIs stressed the need for institutional support and compensation models that acknowledge their role in adapting and supervising AR instruction. Informed by the practical insights of CFIs, this study offers guidance for advancing AR adoption in GA training and underscores the need for system-level strategies to ensure its sustainable and equitable implementation.

Chapter 8

Integrative Synthesis, Implications, and Conclusion

8.1 Introduction

This dissertation set out to critically examine how early-stage GA pilot training can be transformed to become more sustainable, instructionally effective, and technologically progressive. Recognizing longstanding gaps in environmental accountability, pedagogical robustness, and technology adoption within GA training, this work pursued a multidimensional research agenda. Through six integrated studies, it explored the environmental footprint of flight training, evaluated perceptions of current instructional practices, assessed willingness to embrace simulation and AR technologies as assistive training tools, and empirically validated the instructional viability of AR in both simulated and real-world training contexts.

This final chapter synthesizes the overarching findings, identifies key theoretical and practical implications, highlights contributions to knowledge, discusses broader limitations—distinct from the study-specific limitations previously addressed, proposes directions for future research, and concludes with reflective remarks that reconnect to the dissertation’s original motivations.

8.2 Synthesis of Findings and Quantitative Extension

8.2.1 Cross-Study Synthesis of Major Findings

Across the six studies, several central themes emerged:

- **Environmental Sustainability in GA Training:** Study 1 highlighted the significant, yet often overlooked, emissions generated by ab initio flight training. Approximately 30,000 tonnes of CO₂ emissions annually were attributed to PPL and CPL training activities in Canada, underscoring the urgent need for environmentally sustainable alternatives such as simulation-based training, electric aircraft, and sustainable aviation fuels.
- **Limitations of Current GA Pilot Licensing Framework:** Study 2 revealed critical limitations in Canada’s traditional hours-based pilot licensing framework. While accumulating flight time remains the primary regulatory metric for licensing progression, the study found it to be an incomplete and often misleading indicator of true pilot competence. Experienced pilots expressed clear skepticism, emphasizing that proficiency in cognitive, procedural, and decision-making skills cannot be reliably inferred from flight hours alone. Broader systemic shortcomings also emerged around outdated instructional methods, inconsistent assessment practices, and

limited integration of modern technologies. These findings underscored the urgent need for competency-based licensing reforms, enhanced instructional relevance, and greater standardization in GA training to better align with the evolving operational complexities of modern aviation.

- **Technology Acceptance and Readiness for Innovation:** Study 3 demonstrated a cautious but notable openness among GA student and licensed pilots toward integrating simulation (FSTDs) and immersive technologies (AR) as assistive tools for ab initio training. However, barriers including regulatory inertia, cost concerns, and cultural conservatism were identified as obstacles to wider adoption.
- **Instructional Promise of AR:** Studies 4 and 5 empirically validated AR's instructional utility in both high-fidelity simulator and real aircraft environment. AR was shown to enhance procedural learning, support cognitive engagement, and offer scalable, self-paced training pathways, though usability and ergonomic limitations were identified, highlighting areas that will need to be addressed to support effective training integration.
- **Instructor Perspectives as a Critical Enabler:** Study 6 emphasized that CFIs could play a pivotal role in AR's successful integration. Their insights highlighted not only pedagogical potential but also pragmatic concerns around ergonomics, content authoring complexity, and institutional support requirements.

Together, these findings suggest that sustainable, competency-centered, and technology-enhanced reform in GA pilot training is both necessary and feasible—provided that systemic, instructional, and infrastructural barriers are thoughtfully addressed.

8.2.2 Potential for CO₂ Emissions Reduction through FSTD and AR Integration

Building directly on the environmental insights from Study 1, this section extends those findings by exploring the potential for CO₂ emissions reduction through the strategic integration of FSTD and AR-based training technologies within GA pilot education.

FSTDs, as supported by insights from Studies 2 and 3, when used to supplement in-aircraft instruction, can offer effective procedural and cognitive skills training without incurring the environmental cost of real flight operations. Similarly, AR-assisted training, as validated in Studies 4, 5, and 6, presents promising opportunities to reinforce procedural memory and decision-making skills through structured, self-paced training outside the cockpit environment—albeit with usability, ergonomic, and adoption challenges that must be addressed to support effective integration. While neither FSTDs nor AR are substitutes for core

flight experience, their integration into pilot training, particularly early-stage procedural training could meaningfully reduce unnecessary engine operations, taxiing, and minor training sorties that cumulatively contribute to CO₂ emissions.

Although this research did not directly measure reductions in total training hours, emissions, or costs, the findings suggest that with appropriate curriculum redesign, regulatory support, and instructor training, there is potential for these tools to gradually reduce the frequency of low-complexity sorties, idle engine operations, or taxiing tasks performed solely for instructional reinforcement. In turn, such reductions could contribute incrementally to lower CO₂ emissions across the broader training pipeline.

Rather than claiming immediate emissions savings, this work proposes that FSTD and AR integration be considered part of a longer-term sustainability strategy, one that aligns instructional innovation with environmental stewardship goals. Future research could focus on empirically measuring the total training hours, financial costs, and associated CO₂ emissions required for student pilots to achieve defined competency milestones (e.g., PPL or CPL attainment) under both traditional training model and those incorporating FSTD and AR-based instruction. Such comparative studies could help quantify the environmental benefit accordingly.

8.2.3 Visualizing Integrative Research Value

To consolidate the central findings of this dissertation, Figure 30 presents a visual synthesis that captures the thematic integration of the six studies. It illustrates how three critical domains—environmental sustainability, instructional innovation, and technology adoption—intersect to support system-level transformation in GA pilot training.

Although these domains are often explored independently in aviation research, this dissertation demonstrates their interdependence in shaping effective, forward-looking training environments. The integration underscores how GA flight instruction—particularly during the ab initio phase—can serve as a strategic entry point for embedding sustainable practices, advancing pedagogical reform, and leveraging simulation and immersive technologies such as FSTDs and AR.

By representing this intersection visually, Figure 30 encapsulates the dissertation's value proposition, reinforces the coherence of its multidisciplinary inquiry, and provides a conceptual anchor for the implications and recommendations that follow.



Figure 30. Visual integration of findings

8.3 Implications

8.3.1 Theoretical Implications

This dissertation advances the theoretical discourse in several areas:

- **Sustainability in GA Education:** GA remains a particularly underexplored sector in sustainability research, and this dissertation narrows its focus specifically to flight training operations within GA. By systematically quantifying emissions associated with these activities, it extends the sustainability discourse beyond commercial air transport into the domain of GA pilot education and training—an area that has historically been marginalized in broader environmental discussions.
- **Instructional Design for GA Pilot Training:** This work challenges the adequacy of flight-hour accumulation as a proxy for competence, aligning conceptually with the competency-based and evidence-based training (CBTA/EBT) paradigms advocated by international aviation agencies, including ICAO and IATA.
- **Technology Integration in GA Pilot Training:** This work refines understanding of technology acceptance in GA education by providing empirical data on how simulation and immersive

technologies like AR are perceived within resource-constrained, high-stakes training contexts such as GA. It highlights that while there is notable receptivity toward these technologies, adoption barriers—including regulatory flexibility, cost concerns, and entrenched training norms—must be addressed to fully realize their instructional potential.

8.3.2 Practical Implications

From a practical perspective, several actionable insights emerge:

- Flight Training Institutions should more aggressively integrate FSTDs to supplement in-aircraft instruction—particularly for procedural and cognitive skill development—and could cautiously explore the use of emerging immersive technologies such as AR. However, subject to regulatory approval, the adoption of AR should proceed through a phased, piloted, and evaluative implementation strategy to ensure alignment with established training standards, learner needs, and operational requirements.
- Regulatory Authorities could revisit licensing frameworks to recognize simulation and immersive learning hours toward total training requirements, incentivizing adoption of sustainable practices.
- Curriculum Developers could design flexible, modular training paths that blend traditional instruction with adaptive, technology-enabled modalities to better prepare student pilots for contemporary operational environments.
- Instructor Training Programs must incorporate change management and technology fluency modules to empower CFIs to lead innovation in flight training delivery.

8.4 Contributions to Knowledge

This dissertation makes several novel contributions:

- Introduced the first empirically grounded estimation framework for quantifying CO₂ emissions from ab initio pilot training in Canada.
- Provided learner- and practitioner-based evaluations of current pilot licensing practices, exposing systemic instructional shortcomings.
- Extended technology acceptance literature by empirically examining perceptions of FSTDs and AR in GA settings, a traditionally conservative and under-researched domain.

- Developed and validated learner-centered experimental methodologies for evaluating AR's instructional potential in simulated and real-aircraft environments.
- Brought forward instructor-centric perspectives on AR feasibility, highlighting the institutional and ergonomic considerations often overlooked in innovation discussions.

By addressing gaps in sustainability, instructional theory, and technology adoption within GA pilot training, this work offers a comprehensive, multi-dimensional blueprint for future research, regulatory advancement, and instructional practice.

8.5 Limitations

While this dissertation presents significant contributions, several limitations warrant acknowledgment:

- **Contextual Scope:** The studies were conducted within Canadian GA training environments. Caution is required in generalizing findings globally, especially to regions with different regulatory, economic, and training ecosystems.
- **Focus on Ab Initio Stage:** The work concentrates on early-stage training and does not address advanced or recurrent training practices, which may have different instructional dynamics.
- **Technology Maturity:** Evaluations of AR were based on a specific commercially available HMD platform at the time of study. Technological advancements may address some of the usability and ergonomic challenges identified.
- **Participant Sampling:** While efforts were made to recruit diverse participants, the sample sizes—though reasonable for exploratory and experimental work—may not fully reflect the demographic, experiential, or gender diversity present within the wider GA training community.

Recognizing these limitations offers important boundaries for interpreting the findings and highlights areas for refinement in future work.

8.6 Future Research Directions

Building upon this dissertation's findings, several promising avenues for future research emerge:

- **Cross-National Comparative Studies:** Investigate how sustainability practices, instructional innovations, and technology acceptance vary across different national GA training frameworks.
- **Longitudinal Studies on AR Efficacy:** Examine the long-term impact of AR integration on skill retention, safety performance, and career progression among GA student pilots.

- Competency-Based Simulation Curricula: Develop and empirically validate simulation and AR-based curricula aligned with CBTA/EBT standards for ab initio training.
- Cost-Benefit Analyses of AR Integration: Quantify the financial, operational, and environmental return on investment for integrating AR technologies into flight training institutions.
- Instructor Professional Development Models: Explore frameworks for upskilling CFIs to design, deliver, and evaluate immersive learning experiences effectively.
- Sustainable Aviation Ecosystem Design: Future research could investigate how pilot training practices, advancements in aircraft technology (e.g., electric and hybrid-electric aircraft), and regulatory and policy frameworks can be co-optimized to support the development of a fully sustainable GA ecosystem.

8.7 Concluding Remarks

This dissertation began with a simple but profound motivation: to examine whether early-stage GA pilot training could evolve to meet the twin imperatives of environmental responsibility and instructional excellence in a rapidly changing GA training landscape.

Through a carefully structured sequence of studies, this research identified critical gaps, surfaced learner- and practitioner-based experiences, validated emerging instructional technologies, and proposed pathways for modernizing ab initio pilot education. Collectively, it advances a vision of GA pilot training that is not only safer and more effective but also more sustainable and technologically responsive.

As the broader civil aviation sector faces escalating pressures from environmental, operational, and workforce demands, the insights presented here advocate for a proactive, evidence-based approach to training reform. Ultimately, ensuring the resilience and relevance of GA education will depend on our collective willingness to embrace innovation, center learner and instructor experiences, and commit to sustainability as a foundational principle—not just an aspirational goal.

It is hoped that the findings, practices, and reflections offered in this dissertation will contribute meaningfully to this ongoing transformation.

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Appendices

Appendix A: Data from Study 1

Table A1 displays data sourced directly from Transport Canada for the number of private and commercial pilot licenses issued over a 23-year period (2000–2022)

Table A1. Historical issuances of licenses in Canada

Year	Private Pilot License (PPL)	Commercial Pilot License (CPL)
2000	2965	1440
2001	3130	1428
2002	3071	1280
2003	2641	1164
2004	2332	1032
2005	2262	906
2006	2184	871
2007	2349	1085
2008	2692	1270
2009	2700	1390
2010	2420	1626
2011	2321	1373
2012	2468	1207
2013	2305	1098
2014	2568	1103
2015	2813	1310
2016	2705	1128
2017	2842	1345
2018	2749	1630
2019	3052	1747
2020	2191	1400
2021	2561	1513
2022	2251	1515

Appendix B: Data from Study 2

The Table A2 presents participant responses to the Likert scale questions that were included in the survey, each rated on a 5-point scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). Intermediate values represent: 2 (Disagree), 3 (Neither Agree nor Disagree), and 4 (Agree). The response data for each participant is presented in the same order as the questions listed below:

Q1: Flight time or total flight experience (accumulated flying hours) is a reasonable method to quantify pilot competence.

Q2: High-quality flight training could result in improved acquisition of the necessary knowledge, skills, and abilities to fly an aeroplane versus flight training that focuses simply on the number of hours flown.

Q3: From an instructional and learning context with respect to current flight training standards for both dual instruction training and solo flying, there exist limitations that potentially impact the training outcomes.

Q4: Aside from limitations identified previously (if any), current flight training standards adequately serve training needs and ensure satisfactory proficiency in technical and non-technical flying competencies.

Q5: Flight test assessment and evaluation are conducted objectively, with a minimal degree of subjectivity.

Table A2. Participant responses to Likert scale survey questions

Participant	Q1	Q2	Q3	Q4	Q5	Participant	Q1	Q2	Q3	Q4	Q5
1	2	5	4	2	2	101	2	4	3	2	4
2	3	5	5	3	3	102	3	5	5	2	3
3	5	4	4	4	2	103	3	2	2	5	2
4	4	4	3	3	3	104	3	4	4	2	3
5	4	5	3	2	4	105	1	5	4	3	3
6	4	5	4	4	2	106	3	3	2	4	4
7	1	4	3	4	5	107	1	4	4	1	2
8	4	5	4	4	5	108	2	4	4	3	3
9	3	5	4	5	5	109	2	4	3	4	2
10	5	4	4	4	4	110	5	4	4	4	3
11	3	5	5	4	4	111	4	4	3	4	4
12	3	4	4	1	2	112	5	4	4	4	3
13	3	4	3	4	4	113	1	4	4	3	4
14	2	5	1	4	4	114	1	4	4	2	2
15	2	4	3	4	3	115	3	4	4	2	2
16	3	5	4	2	4	116	2	4	4	4	3
17	4	5	4	3	4	117	2	4	4	4	4
18	2	5	4	2	4	118	2	4	4	2	2
19	4	4	3	4	5	119	5	4	4	2	4
20	2	4	3	4	3	120	5	4	4	2	4
21	5	4	4	3	4	121	1	4	4	2	2
22	2	1	2	2	2	122	1	5	4	1	2
23	2	5	4	2	2	123	2	4	4	2	2
24	4	3	4	4	5	124	3	4	4	3	2
25	2	5	4	3	3	125	4	4	4	4	2
26	5	4	4	3	4	126	4	4	4	4	4

27	4	2	5	3	4	127	4	5	4	4	4
28	4	4	5	2	3	128	4	4	4	4	4
29	4	4	4	2	2	129	1	4	4	2	2
30	4	4	4	3	4	130	2	5	3	1	3
31	2	4	4	2	4	131	4	4	4	4	5
32	4	4	4	3	3	132	1	5	4	2	2
33	2	4	4	4	3	133	3	5	5	4	3
34	2	4	4	2	4	134	4	2	3	4	2
35	3	5	5	4	5	135	2	4	4	4	2
36	1	5	3	4	4	136	2	5	5	4	4
37	4	5	4	2	4	137	1	5	5	4	3
38	4	2	4	4	4	138	3	5	5	4	4
39	1	2	4	1	4	139	4	4	4	2	4
40	5	3	3	4	3	140	4	4	4	2	4
41	2	4	4	4	4	141	1	4	3	3	4
42	3	4	4	3	3	142	4	4	4	4	4
43	2	5	4	2	3	143	4	3	3	4	4
44	5	4	4	2	4	144	1	4	4	2	2
45	4	5	5	1	2	145	4	5	4	2	4
46	4	5	4	4	4	146	1	4	2	4	5
47	4	4	4	2	2	147	2	4	4	3	2
48	4	4	3	4	4	148	1	4	4	2	2
49	5	5	4	2	4	149	4	5	5	3	2
50	4	5	3	4	4	150	1	4	4	2	2
51	2	5	4	2	4	151	2	2	4	2	5
52	2	5	4	2	4	152	2	5	3	4	4
53	2	4	4	4	3	153	2	5	3	4	4
54	2	4	4	2	2	154	4	5	5	2	4
55	4	4	4	2	4	155	2	5	3	4	4
56	2	4	4	2	4	156	4	1	4	2	3
57	4	5	4	4	5	157	1	4	4	2	2
58	2	4	4	2	4	158	2	4	4	2	2
59	2	4	4	2	4	159	4	2	2	4	3
60	2	4	4	4	4	160	2	4	4	2	2
61	4	4	4	4	4	161	2	4	4	2	2
62	2	4	4	4	4	162	4	4	4	4	4
63	2	5	4	4	4	163	2	4	4	2	2
64	2	4	4	4	4	164	2	4	4	2	2
65	4	4	3	4	4	165	4	4	3	4	4
66	1	4	3	2	2	166	2	4	4	2	2
67	2	4	4	2	2	167	1	5	5	1	2
68	1	4	3	2	2	168	1	3	4	3	3
69	1	4	3	2	2	169	4	5	3	4	4
70	4	4	4	2	2	170	1	5	5	1	2
71	3	4	4	2	2	171	2	5	5	2	2
72	4	4	4	2	2	172	4	5	3	4	4
73	2	4	4	2	2	173	4	4	3	2	2
74	2	4	3	4	4	174	2	4	4	2	2
75	4	4	4	2	2	175	2	5	5	2	2
76	2	4	4	2	2	176	2	4	4	2	2
77	1	5	4	2	2	177	2	5	4	1	2
78	2	4	4	2	2	178	2	5	5	5	2
79	2	4	4	2	2	179	1	5	5	1	2
80	4	4	3	3	3	180	2	4	4	4	2
81	2	4	4	2	2	181	2	4	4	2	2
82	2	4	4	3	2	182	2	5	5	5	2

83	4	4	3	3	3	183	2	5	4	2	2
84	3	4	2	4	4	184	1	4	3	4	4
85	3	5	4	4	5	185	2	4	4	2	2
86	4	4	3	3	3	186	2	5	4	2	3
87	2	4	4	3	2	187	2	5	4	3	3
88	4	5	5	4	2	188	2	4	4	2	2
89	2	4	4	3	3	189	2	5	4	2	2
90	4	4	3	3	3	190	4	5	3	4	4
91	2	4	4	2	2	191	2	4	4	2	2
92	2	4	4	2	2	192	2	5	5	5	2
93	5	4	3	3	4	193	3	5	3	4	3
94	5	4	3	3	4	194	2	4	4	4	2
95	2	5	4	3	5	195	2	4	4	2	2
96	2	5	4	2	2	196	4	5	3	4	4
97	4	4	3	2	2	197	2	4	4	4	2
98	1	4	4	2	5	198	2	5	3	4	5
99	2	5	4	2	4	199	2	4	4	2	4
100	3	1	1	3	3	200	1	4	4	2	4
						201	5	4	3	2	4
						202	2	4	4	2	4
						203	4	4	4	4	4
						204	1	4	4	3	4
						205	2	4	4	2	2
						206	1	5	4	1	2

Appendix C: Data from Study 3

The Table A3 presents participant responses to the Likert scale questions that were included in the survey, each rated on a 5-point scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). Intermediate values represent: 2 (Disagree), 3 (Neither Agree nor Disagree), and 4 (Agree). The response data for each participant is presented in the same order as the questions listed below:

Q1: In context of the current flight training standards, increased use of flight simulation training devices (FSTD) can provide student pilots an opportunity to strengthen flight competencies and gain higher proficiency to manage routine (normal) flight operations; while also, creating potential for reduced training time and cost.

Q2: Emergency or non-normal scenario training conducted in a FSTD could enable student pilots practice for surprise habituation and provide an opportunity to gain proficiency in handling unexpected or novel events.

Q3: Assistive technology such as augmented reality (AR), delivered through head-mounted display (HMD), can enhance the real-world environment by superimposing digital information such as text, graphics, videos, or voiceovers directly onto operational spaces like the flight deck. This integration provides continuous access to essential data and instructional guidance. Despite limitations like cost or the need for usability training, such technology, when used for flight training in FSTDs, could create a dynamic and immersive environment with significant potential to improve learning.

Table A3. Participant responses to Likert scale survey questions

Participant	Q1	Q2	Q3	Participant	Q1	Q2	Q3
1	5	5	5	101	4	4	4
2	4	4	5	102	4	4	4
3	4	5	5	103	4	4	4
4	4	4	4	104	4	4	4
5	4	3	3	105	4	4	4
6	4	4	4	106	5	5	4
7	1	3	3	107	4	4	5
8	4	4	2	108	4	4	4
9	5	5	3	109	5	5	4
10	1	1	3	110	4	4	4
11	4	4	4	111	4	4	4
12	4	4	4	112	4	4	4
13	4	4	3	113	4	4	5
14	4	4	5	114	4	4	4
15	4	4	4	115	5	5	4
16	4	4	4	116	5	4	4
17	4	4	4	117	4	5	3
18	5	5	3	118	4	5	4
19	3	4	2	119	2	4	4

20	5	5	5	120	3	4	3
21	2	4	4	121	4	3	2
22	4	2	3	122	5	5	5
23	5	5	4	123	3	5	5
24	3	4	3	124	2	4	4
25	5	5	4	125	4	4	5
26	4	4	4	126	4	4	5
27	4	4	4	127	4	4	3
28	4	4	3	128	5	5	4
29	4	4	4	129	4	4	5
30	4	4	4	130	5	5	4
31	5	5	4	131	5	5	4
32	4	5	4	132	5	5	4
33	4	4	4	133	5	5	4
34	5	5	5	134	5	5	4
35	4	5	4	135	5	5	4
36	4	4	4	136	5	5	4
37	4	5	4	137	4	4	4
38	5	4	4	138	4	5	4
39	4	5	4	139	4	5	4
40	5	5	4	140	4	5	3
41	5	4	4	141	4	4	5
42	4	4	4	142	4	4	3
43	5	5	5	143	4	4	4
44	4	5	5	144	4	4	3
45	4	5	5	145	4	4	5
46	4	5	4	146	4	4	4
47	5	5	5	147	4	4	4
48	5	4	4	148	5	5	5
49	2	4	4	149	4	4	3
50	5	5	5	150	4	4	4
51	4	4	3	151	5	4	3
52	2	4	4	152	4	4	4
53	4	3	5	153	4	4	4
54	4	4	4	154	4	4	4
55	4	4	4	155	4	3	2
56	5	5	3	156	3	3	2
57	5	5	5	157	4	4	4
58	4	4	5	158	5	5	5
59	4	4	4	159	3	4	1
60	4	4	4	160	4	4	4
61	4	4	4	161	2	4	2
62	5	5	5	162	4	5	3
63	4	4	2	163	4	5	5
64	1	5	3	164	4	5	5
65	4	4	1	165	4	4	4
66	4	4	3	166	4	5	5
67	4	4	4	167	4	4	4
68	4	4	4	168	5	5	4
69	4	4	4	169	2	4	4
70	3	4	4	170	4	4	5

71	4	5	2	171	5	4	5
72	4	4	4	172	5	5	3
73	1	5	3	173	4	4	4
74	4	4	4	174	5	5	3
75	4	4	4	175	5	5	3
76	4	4	4	176	5	5	4
77	4	5	4	177	5	5	4
78	4	4	4	178	3	4	5
79	4	5	4	179	5	5	4
80	4	4	4	180	5	5	4
81	4	5	4	181	4	5	4
82	4	4	4	182	4	5	4
83	5	5	4	183	4	5	4
84	4	4	4	184	4	4	3
85	5	5	3	185	4	5	4
86	4	5	3	186	4	4	4
87	4	5	4	187	4	4	4
88	3	5	5	188	4	4	4
89	5	5	4	189	5	5	4
90	5	5	4	190	5	5	4
91	4	4	4	191	5	5	4
92	5	5	5	192	4	5	4
93	4	5	4	193	4	4	4
94	4	5	4	194	4	5	4
95	3	4	4	195	4	5	4
96	4	5	5	196	4	5	3
97	4	5	4	197	3	3	4
98	2	4	3				
99	5	4	5				
100	5	5	4				

Appendix D: Post-Study Questionnaires Completed by Participants in Studies 4 and 5

Tables A4–7 present the post-study questionnaires completed by participants in Studies 4 and 5 for each training condition (AR and paper-based). These instruments captured participants’ experiences across workload, situational awareness, technology acceptance, and sickness symptoms.

Table A4. NASA-TLX Workload Assessment Questionnaire, where Each Dimension was Rated on a Scale from 0 (Low) to 10 (High) [304–306]

Dimension	Rating (0-10)
Mental Demand: Assesses how much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.). Was the task mentally demanding? Did it require a lot of thinking? E.g. A low rating can indicate that assistance likely reduced the mental effort required to understand and perform the task.	
Physical Demand: This measures the amount of physical activity required (e.g., pushing, pulling, turning, controlling, activating, etc.). How physically demanding was the task? E.g. A low rating can indicate that assistance likely minimized the physical effort needed to perform the task.	
Temporal Demand: This evaluates the time pressure felt to accomplish the task. Did you have to work quickly? Was the pace of the task fast? E.g. A low rating can indicate that assistance likely exerted less pressure to complete the task quickly, indicating a low temporal demand.	
Performance: This assesses perception of how successful you were in achieving the goals of the task. Were you satisfied with your performance? E.g. A lower score here indicates better perceived performance and vice versa. This inversely rated dimension would reflect the participant's perception of their success in completing the task.	
Effort: This measures the level of work you felt was needed to accomplish your level of performance. How hard did you have to work to achieve your level of performance? E.g. A low rating can indicate that assistance likely made the task easy to manage, the effort required to achieve high performance would be perceived as minimal, leading to a low effort rating.	
Frustration Level: This assesses how irritable, stressed, and annoyed versus content, relaxed, and complacent you felt during the task. E.g. A low rating can indicate that assistance likely made the task easy to manage resulting in minimal frustration, task was found to be straightforward and free from irritating difficulties.	

Table A5. SART Situational Awareness Questionnaire, with Each Dimension Rated on a Scale from 0 (Low) to 7 (High) [301,307–310]

Dimension		Rating (0-7)
Demand	Instability of the Situation: Reflects how much the situation changed unpredictably during the task. E.g., a low rating may indicate that the situation felt relatively stable and predictable, possibly because the assistance effectively mitigated unexpected changes. Real-time cues or structured guidance may have smoothed transitions, allowing you to stay focused without needing to constantly adapt to sudden shifts.	
	Complexity of the Situation: Evaluates how intricate or multifaceted the task felt. E.g., a low rating can suggest that assistance simplified complex decision-making by visually or contextually organizing key task elements, making overall situation feel more manageable.	
	Variability of the Situation: Assesses how many factors or parameters changed during the task. E.g., a low rating may suggest that the situation remained consistent, likely due to the assistance minimizing distractions or filtering out unnecessary changes. The guidance may have presented only the most relevant updates, making the task feel more stable and easier to manage without overwhelming shifts in focus.	
Supply	Arousal (Alertness and Engagement): Captures your physiological and psychological readiness and engagement with the task. E.g., a high rating may suggest that the assistance maintained your alertness by making the task engaging without causing stress or overexcitement—keeping you attentive but not anxious.	
	Concentration of Attention: Measures how focused your attention had to be on parts of the task. E.g., a low rating may indicate that the task did not require intense focus on specific elements, possibly because the assistance distributed attention across the task in a balanced way. This could mean the system simplified decision-making or automated routine elements, reducing the need for sustained concentration on any one area.	
	Diversion of attention: Assesses the distribution or spread of focus across multiple elements. E.g., a low rating may suggest that the task required minimal shifting of attention between different elements, potentially because the assistance consolidated relevant information into a central focus area. This could indicate that the support reduced the need for multitasking, allowing you to stay anchored on a single, high-priority aspect of the task.	
	Supply of Attentional Resources (Spare Mental Capacity): Measures how much cognitive capacity you had left while completing the task. E.g., a high rating may suggest that the assistance supported you in organizing task elements or anticipating actions, freeing up your attention to manage additional inputs or unexpected developments more comfortably.	
Understanding	Information Quantity: Assesses whether the amount of information you received was sufficient. E.g., a high rating may indicate that the assistance likely provided an appropriate amount of information—enough to act confidently but not so much that it caused cognitive overload.	

	Information Quality: Evaluates the usefulness, clarity, and accuracy of the information received. E.g., a high rating could mean that the assistance delivered clear, precise, and actionable guidance—improving your understanding and reducing decision uncertainty.	
	Familiarity with the Situation: Measures how well you felt you understood the environment or task. E.g., a high rating could suggest that assistance likely made unfamiliar elements feel more accessible, possibly through visual cues, structured walkthroughs, or progressive disclosure—resulting in increased confidence and reduced cognitive friction.	

Table A6. TAM Technology Acceptance Questionnaire, with Each Item Rated on a Scale from 0 (Strongly Disagree) to 7 (Strongly Agree) [311–313]

Dimensions		Rating (0-7)
Usefulness	Work More Quickly: Does the technology help you complete tasks faster than without it? Consider if the augmented reality (AR) assistance allows you to finish tasks more swiftly compared to using paper-based instructions. Job Performance: Assess whether the technology helps you perform your job with higher quality. Does the AR-based assistance improve the accuracy or quality of your work compared to traditional methods? Increase Productivity: Think about whether the technology enables you to accomplish more tasks in the same amount of time. Does the AR assistance help you manage more tasks effectively compared to paper-based assistance? Effectiveness: Evaluate how well the technology supports achieving your goals. Is the AR-based assistance more effective in guiding you through procedures than paper instructions? Makes Job Easier: Determine if the technology simplifies your work. Does using AR make understanding and following procedural tasks easier compared to traditional paper-based methods? Useful: This is a general assessment of the technology's overall utility. Do you find AR-based assistance to be more beneficial for your work than paper-based assistance?	

Ease of Use	Easy to Learn: Consider how quickly and easily you can begin effectively using the technology. Is the AR system straightforward to learn compared to understanding paper-based instructions? Controllable: Evaluate how much control you feel you have over the technology. Can you easily manipulate the AR interface or navigate through information as needed, more so than with paper instructions? Clear & Understandable: Assess how clearly the technology presents information. Is the information provided by the AR system more comprehensible than that on paper? Flexible: Consider the technology's adaptability to different tasks or conditions. Is the AR system more adaptable to various procedural tasks compared to static paper instructions? Easy to Become Skillful: Think about the ease with which you can become proficient in using the technology. Is it easier to master using the AR system than to become efficient with paper-based methods? Easy to Use: This is an overall evaluation of how user-friendly the technology is. Do you find the AR-based assistance to be more straightforward to use than traditional paper-based instructions?	
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Table A7. SSQ Simulator Sickness Questionnaire, with Each Symptom Rated on a Scale from 0 (Symptom Not Experienced) to 3 (Severe) [292,314–316]

SSQ Item	Score (0–3)
1. General discomfort	
2. Fatigue	
3. Headache	
4. Eyestrain	
5. Difficulty focusing	
6. Increased salivation	
7. Sweating	
8. Nausea	
9. Difficulty concentrating	
10. Fullness of head	
11. Blurred vision	
12. Dizzy (eyes open)	
13. Dizzy (eyes closed)	
14. Vertigo	
15. Stomach awareness	
16. Burping	

Appendix E: Data from Study 4

The Table A8 presents composite scores for each participant across the four measures: NASA-TLX (workload), SART (situational awareness), TAM (technology acceptance), and SSQ (simulator sickness), under both AR and paper-based training conditions. These scores were derived by aggregating ratings across the individual dimensions of each measure, representing each participant's overall experience with the respective training modality.

Table A8. Composite scores for NASA-TLX (workload), SART (situational awareness), TAM (technology acceptance), and SSQ (simulator sickness)

Participant	NASA-TLX		SART		TAM		SSQ	
	AR	Paper	AR	Paper	AR	Paper	AR	Paper
1	33.3	48.3	5.8	3.8	5.9	4.0	156.4	0.0
2	55.0	60.0	6.9	2.9	5.7	3.5	293.5	156.4
3	21.7	96.7	9.2	3.9	7.0	4.1	92.4	0.0
4	25.0	78.3	6.2	2	7.0	3.6	0.0	56.7
5	35.0	56.7	7.8	3.9	6.2	2.9	0.0	108.8
6	30.0	83.3	5.9	2.5	7.0	1.6	172.8	340.9
7	38.3	55.0	6.7	1.9	6.9	1.1	0.0	0.0
8	41.7	66.7	6.9	1.7	4.3	4.3	196.5	0.0
9	33.3	78.3	5.8	2.8	5.3	3.0	28.3	28.3
10	30.0	66.7	8.2	2.1	6.4	3.7	208.5	0.0
11	35.0	41.7	6.8	4.3	6.5	3.8	0.0	0.0
12	28.3	73.3	4.8	3.4	5.7	4.3	108.8	64.0
13	35.0	71.7	7.2	3.6	5.6	4.7	92.4	0.0
14	38.3	58.3	7.6	5	6.2	4.6	92.4	80.4
15	33.3	65.0	7.1	3.6	5.0	2.0	149.1	201.1
16	41.7	53.3	6	3.5	7.0	2.9	0.0	108.8
17	25.0	51.7	6.6	1.8	5.1	2.8	0.0	0.0
18	28.3	41.7	7.2	4.3	6.2	3.7	0.0	0.0
19	43.3	80.0	6.2	3.1	5.9	4.3	236.8	412.3
20	33.3	53.3	5.5	3	4.7	3.8	213.1	85.0
21	36.7	58.3	5	2.3	6.5	4.3	236.8	172.8
22	31.7	46.7	6.7	4.7	5.8	4.7	80.4	196.5
23	71.7	61.7	4.6	5.8	4.5	4.5	172.8	108.8
24	33.3	61.7	6.9	4.1	5.8	4.4	149.1	137.1
25	28.3	51.7	6.6	4.1	6.2	2.3	120.7	0.0
26	36.7	75.0	7.6	3.5	5.8	2.2	0.0	0.0
27	51.7	75.0	7.3	3.1	5.9	3.8	28.3	56.7
28	53.3	61.7	5.8	5	5.6	3.3	80.4	28.3
29	45.0	88.3	8.2	2.1	6.8	2.0	64.0	340.9
30	28.3	63.3	5.8	4.1	5.3	3.5	64.0	64.0

The Table A9 summarizes individual participant outcomes from the retention assessment phase under both AR and paper-based training conditions. It includes the number of instructor-provided assists during the task, the number of retention errors made, and the overall retention assessment outcome. These values were directly recorded from participants' observed task performance and instructor input.

Table A9. Participant outcomes from retention assessment

Participant	Number of Assists Provided		Memory Retention Errors		Overall Retention Assessment Outcome	
	AR	Paper	AR	Paper	AR	Paper
1	1	5	4	3	Partial Success	Partial Success
2	1	4	2	6	Partial Success	Partial Success
3	2	4	4	2	Partial Success	Partial Success
4	3	6	5	4	Partial Success	Partial Success
5	1	3	4	2	Partial Success	Partial Success
6	3	4	5	4	Partial Success	Partial Success
7	3	7	5	3	Partial Success	Partial Success
8	0	6	2	6	Partial Success	Partial Success
9	2	5	5	3	Partial Success	Partial Success
10	2	4	3	5	Partial Success	Partial Success
11	3	5	7	9	Failure	Failure
12	2	4	3	2	Partial Success	Partial Success
13	3	5	2	2	Partial Success	Partial Success
14	1	6	2	1	Partial Success	Partial Success
15	3	8	2	1	Partial Success	Partial Success
16	0	2	3	1	Partial Success	Partial Success
17	0	1	2	1	Partial Success	Partial Success
18	0	1	1	0	Partial Success	Complete Success
19	0	1	1	1	Partial Success	Partial Success
20	0	2	2	1	Partial Success	Partial Success
21	0	0	2	1	Partial Success	Partial Success
22	1	0	2	1	Partial Success	Partial Success
23	0	3	2	1	Partial Success	Partial Success
24	0	2	3	1	Partial Success	Partial Success
25	1	2	1	2	Partial Success	Partial Success
26	0	2	2	1	Partial Success	Partial Success
27	0	1	2	1	Partial Success	Partial Success
28	0	2	2	0	Partial Success	Complete Success
29	0	1	1	0	Partial Success	Complete Success
30	0	1	2	1	Partial Success	Partial Success

Appendix F: Data from Study 5

The Table A10 presents composite scores for each participant across the four measures: NASA-TLX (workload), SART (situational awareness), TAM (technology acceptance), and SSQ (simulator sickness), under both AR and paper-based training conditions. These scores were derived by aggregating ratings across the individual dimensions of each measure, representing each participant's overall experience with the respective training modality.

Table A10. Composite scores for NASA-TLX (workload), SART (situational awareness), TAM (technology acceptance), and SSQ (simulator sickness)

Participant	NASA-TLX		SART		TAM		SSQ	
	AR	Paper	AR	Paper	AR	Paper	AR	Paper
1	38.33	56.67	6.60	1.40	5.67	3.17	128.06	28.35
2	43.33	81.67	5.30	2.40	4.50	3.17	120.73	0.00
3	46.67	63.33	5.90	3.50	4.83	3.75	288.88	108.76
4	41.67	70.00	4.20	3.30	4.17	3.17	469.00	589.50
5	50.00	65.00	5.30	2.70	5.17	2.67	336.53	120.73
6	50.00	68.33	6.30	2.80	5.50	3.00	56.70	132.47
7	50.00	43.33	6.40	2.30	5.42	2.92	144.44	64.03
8	55.00	56.67	6.90	1.50	4.83	2.75	201.14	108.76
9	45.00	66.67	6.80	4.90	5.08	2.67	28.35	0.00
10	41.67	70.00	6.00	3.10	5.08	2.33	64.03	288.88
11	43.33	73.33	6.00	4.20	4.08	3.00	144.44	144.44
12	41.67	93.33	7.70	3.00	5.50	2.00	28.35	0.00
13	36.67	56.67	5.70	3.30	5.25	3.25	92.38	132.47
14	50.00	35.00	6.10	2.80	5.17	2.67	92.38	0.00
15	65.00	93.33	7.60	2.40	5.17	2.58	108.76	208.47
16	40.00	88.33	4.80	3.00	4.83	3.08	108.76	52.06
17	38.33	68.33	7.30	5.50	4.33	3.33	224.85	56.70
18	38.33	55.00	3.60	3.30	4.67	3.08	0.00	0.00
19	53.33	75.00	7.30	3.70	5.50	3.75	0.00	80.41
20	61.67	78.33	5.80	3.30	4.33	3.92	184.76	421.35

The Table A11 shows individual participant outcomes from the retention assessment phase under both AR and paper-based training conditions. It includes the number of instructor-provided assists during the task, the number of retention errors made, and the overall retention assessment outcome. These values were directly recorded from participants' observed task performance and instructor input.

Table A11. Participant outcomes from retention assessment

Participant	Number of Instructor-provided Assists		Retention Recall Errors		Overall Retention Assessment Outcome	
	AR	Paper	AR	Paper	AR	Paper
1	1.00	3.00	4.00	2.00	Partial Success	Partial Success
2	0.00	1.00	2.00	0.00	Partial Success	Complete Success
3	0.00	3.00	7.00	4.00	Partial Success	Partial Success

4	0.00	1.00	3.00	2.00	Partial Success	Partial Success
5	0.00	2.00	5.00	3.00	Partial Success	Partial Success
6	0.00	2.00	4.00	4.00	Partial Success	Partial Success
7	1.00	1.00	2.00	1.00	Partial Success	Partial Success
8	0.00	0.00	3.00	1.00	Partial Success	Partial Success
9	0.00	2.00	2.00	4.00	Partial Success	Partial Success
10	0.00	2.00	1.00	3.00	Partial Success	Partial Success
11	0.00	1.00	0.00	0.00	Complete Success	Complete Success
12	0.00	1.00	3.00	4.00	Partial Success	Partial Success
13	0.00	0.00	1.00	0.00	Partial Success	Complete Success
14	0.00	7.00	6.00	7.00	Partial Success	Partial Success
15	0.00	2.00	2.00	3.00	Partial Success	Partial Success
16	0.00	1.00	2.00	1.00	Partial Success	Partial Success
17	0.00	3.00	4.00	2.00	Partial Success	Partial Success
18	0.00	1.00	3.00	5.00	Partial Success	Partial Success
19	2.00	5.00	2.00	4.00	Partial Success	Partial Success
20	0.00	0.00	1.00	1.00	Partial Success	Partial Success