



# Extended reality (xR) flight simulators as an adjunct to traditional flight training methods: a scoping review

Glen Ross<sup>1</sup> · Andrew Gilbey<sup>1</sup>

Received: 13 February 2023 / Revised: 11 September 2023 / Accepted: 25 September 2023 / Published online: 20 October 2023  
© The Author(s) 2023

## Abstract

Over the next 20 years, it is predicted that an additional 760,000 new pilots will be needed to meet the growing demands of the global aviation industry. With current training capability, this may be difficult to achieve. A potential means of improving the efficiency and lowering the cost of flight training, which arguably may be prohibitively expensive to many potential trainee pilots, is to use extended reality simulation in place of traditional flight simulators and aircraft for at least some of the required training. To provide a better understanding of the possibilities in this regard, and where current research has advanced, a scoping review was undertaken. In total, 18 studies were identified as meeting the inclusion criteria. It was concluded that extended reality technology has the potential to be successfully employed in flight training—saving time and money, whilst also enabling increased training capability, although some potential limitations were identified. The interest in this technology, combined with evidence pointing to its potential usefulness in flight training, suggests that further examination in this area by academia and industry is warranted.

**Keywords** Virtual reality · Flight training · Pilot · Aviation · Immerging technology

## Abbreviations

BIP	Break in presence	FTO	Flight Training Organisation
CAA	Civil Aviation Authority (New Zealand)	Haptic	The transmitting and understanding of information through touch
CASA	Civil Aviation Safety Authority (Australian)	HMD	Head mounted display (used with xR technology)
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation	ICAO	International Civil Aviation Organisation
COTS	Commercial Off The Shelf	Immersion	Sensory immersion within a virtual environment
COVID-19	Coronavirus disease 2019	JB	Joanna Briggs Institute
EASA	European Union Aviation Safety Agency	Legacy training equipment Pilot Licence	FTDs, FFSs and aircraft Certification for operating an aircraft—issued by the aviation authority of a country
FAA	Federal Aviation Administration		Mixed reality
FFS	Full flight simulator	MR (mR)	A sense of being in the virtual environment
FI	Flight instructor	Presence	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
FTD	Flight training device	PRISMA	PRISMA for Scoping Reviews
		PRISMA-ScR	Pilot Training Next (USAF initiative)
		PTN	

✉ Glen Ross  
G.Ross@massey.ac.nz  
Andrew Gilbey  
A.P.Gilbey@massey.ac.nz

<sup>1</sup> School of Aviation, Massey University, Palmerston North, New Zealand

Ratings	Flight crew qualification that authorises the holder to operate a particular aircraft or exercise particular privileges
USAF	United States Air Force
US Army	United States Army
US Navy	United States Navy
VE	Virtual environment
VR	Virtual reality
VRFs	Virtual reality flight simulator
XR (xR)	Extended reality

## 1 Introduction

Prior to the COVID-19 pandemic, the global aviation industry was experiencing sustained growth, whilst concurrently suffering from a significant shortage of qualified, experienced pilots [1]. At least part of this shortfall is believed to be due to insufficient training capacity to meet demand, and the prohibitive costs of flight training [1].

Once the industry has recovered from the effects of COVID-19, it is predicted that an additional 260,000 to 350,000 additional pilots will be needed over the next decade [1, 2]. Based on a 20-year fleet forecast for commercial aircraft, aircraft utilisation, attrition rates, and regional crewing differences, this equates to a requirement of up to 763,000 new pilots by 2039 [3].

It takes approximately 24 months to train a multi-engine, instrument-rated commercial pilot [4]. However, as many airlines now require pilots to have a university degree [5], in addition to their licences, ratings and hour requirements, it can now take up to 48 months before a newly qualified pilot graduates flight training. Even then, newly qualified pilots, who only have the minimum hours required to hold a licence, may find it difficult to gain employment without first gaining experience.

Pilots train in both real aircraft and using simulation. Traditional flight simulators are typically expensive (US\$10K to US\$10M) and require specialist simulator staff and flight instructors to assist in their operation [6, 7]. However, extended reality (xR) [including virtual reality (VR) and mixed reality (MR)] is increasingly of interest to the aviation industry for its potential in flight training [8]. xR-based simulators generally do not require specialists to operate and offer student pilots the opportunity to complete at least part of their training in a self-paced, learner-centric, collaborative environment, where autonomy and individualised training are encouraged [9].

By implementing xR technology in the form of virtual reality flight simulators (VRFSSs), time and cost reductions could be made by substituting actual aircraft flying hours

with relatively affordable simulator training [10, 11]. VRFSSs may also have the ability to reduce the scale of operations, specifically in areas such as airport and airways charges, maintenance provision and the quantity of fuel (and other carbon-based materials) consumed, thus simultaneously lowering the costs and the negative environmental impact of aviation training [11–14]. These latter potential advantages would also bring operators in line with environmental initiatives such as ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSA) [15].

Better use of training time allocations, fewer delays or cancellations due to weather, or unavailability of aircraft due to maintenance issues, results in less time required to train pilots. A reduction in airframe hours and fuel usage, less maintenance and a marked reduction in the associated ancillary logistic costs might also lead to additional financial savings. A recent cost–benefit analysis [11] found that the US Air Force (USAF) alone could make savings of tens of billions of US dollars to fixed and variable operating costs over the next decade by implementing xR flight training in the form of the Pilot Training Next (PTN) initiative. It is suggested then that in the civil sector, potential operational savings such as these could be passed on to the consumer in the form of reduced training fees. This in turn could increase the attractiveness of a career in aviation to a broader base of potential student pilots to whom at present the cost of flight training is prohibitively high [16, 17].

In the current scoping review, we seek to systematically collate the current evidence on whether xR technology has the potential to be used as an adjunct to existing flight training methods already employed by civil FTOs worldwide. Our research question, therefore, is ‘What is the nature of the evidence to support the use of extended reality (xR) flight simulators in traditional flight training methods?’ The objectives of the current ScR were to: (1) identify all relevant literature to assist in answering the RQ, and (2) what currently is the body of research and what further research might be required.

This review may assist and guide researchers interested in the use of xR in aviation training to best decide the direction future research might proceed and what is the current state of evidence and the methods that have provided it so far.

## 2 Method

Systematic literature searches of the academic databases, Web of Science, Scopus and Google Scholar were performed via the bibliographic platform EndNote to identify journal articles, conference proceedings, reports and unpublished grey literature that were published in English only relating to the use of xR in aviation. The following Boolean search terms were used: (1) “flight sim\*” AND “virtual reality” OR

“mixed reality” OR “extended reality”; (2) “flight training” AND “virtual reality” OR “mixed reality” OR “extended reality”; (3) “pilot training” AND “virtual reality” OR “mixed reality” OR “extended reality” and (4) “aviation training” AND “virtual reality” OR “mixed reality” OR “extended reality.”

Applying the Joanna Briggs Institute concept of population, concept, context (PCC) protocol [18], inclusion criteria were that study populations should be pilots of an aircraft (qualified or training), aircraft type may be fixed-, rotary-wing, or UAV, the study should employ xR (VR or MR) flight simulation technology and the research should relate to flight training.

Two preliminary screening steps were taken. For Google Scholar search returns only, due to the number of results envisaged to be returned, and as recommended in previous studies [19–21], only the first 150 results were considered for inclusion. Following this, a title-only screening was carried out on all results returned from all sources, to identify returns that were obviously not relevant.

One author (GR) completed the initial database searches, and both authors decided which of the initial search returns satisfied the inclusion/exclusion criteria. The initial review of all studies was undertaken first by GR and then by AG. Any disagreements were to be settled by discussion, or, where agreement could not be reached, a third party independent of the study was to be asked to arbitrate.

Following the full-text review, a data extraction table was populated according to suggestions made in the JBI Reviewer’s Manual [18, 22]. This included data, relating to: author(s), year of publication, title, publication source, country of origin, aims/purpose, population, method, concept, conclusions and key findings (see Tables 1, 2).

### 3 Results

Initial searches returned a total of  $n = 871$  potential studies of interest. After the removal of  $n = 104$  duplicates, screening by title led to a further  $n = 584$  studies being omitted as they were not relevant. The abstracts of the remaining  $n = 183$  were screened, after which a further  $n = 121$  studies were excluded as being not relevant, leaving  $n = 62$  studies identified as of potential or probable interest. Following the full-text screening, a further  $n = 37$  studies were discounted for reasons such as the study was not relevant, the full text was not accessible, or it was not available in the English language. At this point, two further studies were identified and added following a review of the references, meaning  $n = 27$  studies were subjected to the final in-depth full-text screening. During this final stage, a further  $n = 9$  studies were excluded because they were either not relevant, participant ‘ $n$ ’ details were not specific, it was discovered they were

duplicate studies published using a different title or were not empirical. The  $n = 18$  remaining studies were selected for inclusion in the scoping review. No additional studies were acquired as a result of the personal or public requests made to authors, ResearchGate or LinkedIn.

Figure 1 illustrates the stages of the literature search and details the number of studies screened at each stage, including the number of those studies included/excluded

### 4 Characteristics of individual studies

Analysis of the characteristics of individual studies was undertaken by both authors, with any disagreements resolved by discussion. Conference proceedings accounted for  $n = 8$  (44%) of the included studies with only  $n = 2$  (11%) published in peer-reviewed journal articles. All  $n = 18$  of the studies were published since 2018. Of the included studies,  $n = 11$  (61%) of the lead authors were based in the USA,  $n = 3$  (17%) in Canada,  $n = 1$  (5.5%) in Belgium,  $n = 1$  (5.5%) in Germany,  $n = 1$  (5.5%) in Poland and  $n = 1$  (5.5%) in Sweden. In total  $n = 13$  (72%) of the studies used quantitative methods:  $n = 7$  (54%) quasi-experimental,  $n = 3$  (23%) correlational,  $n = 2$  (23%) descriptive and  $n = 1$  (8%) experimental. Ten of the studies used qualitative methods to gather results, with  $n = 7$  (70%) using questionnaires,  $n = 2$  (20%) observations,  $n = 1$  (10%) interviews.

The majority of the included studies,  $n = 11$  (61%), focussed on civilian flight training, with the remaining  $n = 7$  (39%) focussing on military flight training, although interestingly,  $n = 1,099$  (76%) participants were military and  $n = 339$  (24%) were civilian. Of the  $n = 1,438$  participants in the included studies,  $n = 205$  (14%) were qualified pilots, who held a cross-section of licences from PPL to ATPL (or the military equivalent),  $n = 1048$  (73%) were student pilots undergoing formal flight training and  $n = 185$  (13%) were unqualified non-pilot participants under instruction.

A summary of the conclusions and key findings (see Table 1) of the included studies suggested that  $n = 2$  studies (one descriptive, one observational) explicitly reported that xR could offer some degree of cost savings in pilot training and  $n = 4$  (two observational and two descriptive) stated pilot training time could potentially be reduced. Thirteen studies (four quasi-experimental, three qualitative questionnaires, two observational, two descriptive, one correlational and one experimental) reported positive learning experiences, and  $n = 5$  (two correlational, one observational, one quasi-experimental and one descriptive) stated that xR was potentially as good as legacy methods. Although xR could potentially reduce the actual number of flying hours required, it should be remembered that there will be a finite limit to this number as flying a real aircraft is, presently, still a regulatory requirement to gain a pilot licence. In the future, aviation

**Table 1** Data extraction table—publication details

Author/s (base)	Year Pub	Title	Pub type	Aims/purpose	Population/sample size
Pope, T (USA) [11]	2019	A cost-benefit analysis of Pilot Training Next	Department of Operational Sciences, Graduate School of Engineering and Management, Wright-Patterson Air Force Base	To compare legacy undergraduate pilot training (UTP) costs, production and quality to the recently initiated Pilot Training Next (PTN) VR programme through a cost-benefit analysis of cost, production and quality	USAF student pilots (cost-benefit analysis—no numerical data for <i>n</i> of participants)
Sheets, T; Elmore, M (USA) [23]	2018	Abstract to action: Targeted learning system theory applied to adaptive flight training	Air Command and Staff College, Air University, Maxwell Air Force Base	The study takes a practitioner's approach to transforming abstract ideas into actionable options for the future of education and training. Using exploratory and applied design research, the study draws on scientific knowledge and uses technologies to create the idea of the targeted learning systems theory (TLST) using virtual reality learning environments (VRLE)	A convenience sample of 40 USAF participants with various levels of flight experience
Sakib, M; Chaspari, T; Ahn, C; Behzadan, A (USA) [24]	2020	An experimental study of wearable technology and immersive virtual reality for drone operator training	27th International Workshop on Intelligent Computing in Engineering	To analyse drone operator's physiological data (collected by wearable devices) to enable an objective comparison of how VR training resembles real-world situations	25 participants aged 25–30 19 males, 6 females
Dalladaku, Y; Kelley, J; Lacey, B; Mitchiner, J; Welsh, B; Beigh, M (USA) [25]	2020	Assessing the effectiveness of virtual reality in the training of army aviators	2020 Annual General Donald R Keith Memorial Capstone Conference—Society for Industrial and Systems Engineering	To modernise flight training the US Army introduced virtual reality (VR) through the Aviator Training Next (ATN) programme. This programme uses VR to supplement "traditional hands-on" training. ATN's primary goal is to produce aviators of the same quality as those trained via traditional means without adding time	Historic data from 5 traditional flight school classes All ATN classes over 6 months with a subset of 10–15 students from each class randomly selected for participation
Wilson, J; Scielzo, S; Nair, S; Larson, E (USA) [26]	2020	Automatic gaze classification for aviators: Using multi-task convolutional networks as a proxy for flight instructor observation	International Journal of Aviation, Aeronautics, and Aerospace, Embry-Riddle Aeronautical University—Worldwide	Can using eye-tracking (with machine learning) objectively assess aviator scan patterns during training, and thus reduce the instructor's overall workload Two key research questions: 1. Do flight instructors assess the quality of scan patterns of an aviator similarly? 2. If so, can machine learning techniques be used to automate the instructor evaluation of scan pattern quality for aviators in various phases of flight?	40 participants: 21 pilots (all with military flying experience), 9 operators (with some flight or simulation experience), and 10 novices (no aircraft experience at all)
McGowin, G; Xi, Z; Newton, O; Sukthankar, G; Fiore, S; Oden, K (USA) [27]	2020	Examining enhanced learning diagnostics in virtual reality flight trainers	Proceedings of the Human Factors and Ergonomics Society Annual Meeting	Summarise findings from learning and training research that can be adapted to virtual reality to better understand the relationship between learning and transfer Describe where these methods were integrated to study learning and training using a blend of traditional media with virtual reality simulation assessments	23 undergraduate students, 15 male and 8 female 20 participants had little to no familiarity with flight simulators 18 participants rated their video game expertise as fair or less

**Table 1** (continued)

Author/s (base)	Year Pub	Title	Pub type	Aims/purpose	Population/sample size
Ommerli, C (Canada) [28]	2020		Examining the effects of perceived telepresence, interactivity and immersion on pilot situation awareness during a virtual reality flight exercise	Faculty of Graduate and Postdoctoral Affairs, Carleton University	47 participants aged 17–71 Flying experience ranged from 2–12,000 h Participants held a mixture of licences from student to ATP/L military
Lawrynczyk, A (Canada) [12]	2018		Exploring virtual reality flight training as a viable alternative to traditional simulator flight training	School of Computer Science, Carleton University	41 participants, ages 18–32 2 participants were pilots and 1 other had some flying experience 38 participants had no aviation experience 18 participants indicated that they play video games at least once a week
Trimmon, H (Belgium) [14]	2019		Immersive technologies for virtual reality—case study: Flight simulator for pilot training	School of Management, University of Liège	17 participants aged 18–25 8 males 9 females 10 participants had previously experience VR
Pennington, E; Haifer, R; Nistler, E; Seech, T; Tossell, C (USA) [13]	2019		Integration of advanced technology in initial flight training	2019 Systems and Information Engineering Design Symposium	60 cadets from the US Air Force Academy
Lewis J Livingston J (USA) [29]	2018		Pilot Training Next: Breaking institutional paradigms using student-centred multimodal learning	Interservice/Industry Training, Simulation, and Education Conference (IITSEC)	20 student pilots and 13 instructor pilots (IPs) were specifically selected for the experimental programme
Xi, Z; McGowin, G; Fiore, S; Newton, O; Sukthankar, G; Oden, K (USA) [30]	2020		Predicting student flight performance with multimodal features	13th International Conference on Social Computing, Behavioural-Cultural Modelling and Prediction and Behaviour Representation in Modelling and Simulation	23 novice pilots with no prior flight training experience, aged 18–29 15 males 8 females

Table 1 (continued)

Author/s (base)	Year Pub	Title	Pub type	Aims/purpose	Population/sample size
McCoy-Fisher, C; Mishler, A; Bush, D; Severe-Valsaint, G; Natali, M; Riner, B (USA) [31]	2019	Student naval aviation extended reality device capability evaluation	US Naval Air Warfare Centre Training Systems Division	The purpose of this study was to assess the impact of XR on Student Naval Aviator (SNA) training performance outcomes. Specifically, the research team evaluated three virtual reality part-task trainers (VR-PTTs) and one mixed reality visual system (MRVS) on student performance in primary, intermediate jet, and advanced strike training The research team leveraged Kirkpatrick's four levels of training evaluation: (1) reactions, (2) learning, (3) behaviour, and (4) results	966 participants 958 Student Naval Aviators (SNAs) or recently winged pilots 6 instructor pilots (IPs)/pilot training officers (PTO) 1 simulator instructor 1 flight surgeon
Dymora, P; Kowal, B; Mazurek, M; Romana, S (USA) [32]	2021	The effects of virtual reality technology application in the Aircraft Pilot Training Process	IOP Conference Series: Materials Science and Engineering	To obtain the optimal duration of exposure to virtual reality (VR) before the onset of physiological problems for the user that could affect teaching outcomes	17 participants (aged 21–23) 16 males 1 female Participants had no simulation or aviation experience
Whitson, R (USA) [33]	2019	Training in a modern age	Department of Engineering, Arizona State University	To examine the levels of educational applicability for virtual reality in flight simulation training and ascertain if there is a significant difference between VR and training using a standard PC monitor	24 participants aged 20–25 2 groups of 12 participants Varying levels of familiarity with flight simulators and video games only
Gustafsson, A (Sweden) [34]	2018	Use of head-mounted virtual reality displays in flight training simulation	Department of Computer and Information Science, Linköpings Universitet	Comparison between the current capabilities of commercially available VR HMDs to flight training simulators used today. To provide an evaluation of current VR HMD capabilities, a proof-of-concept prototype simulator with basic controls	30 participants 29 simulator engineers (non-pilots) 1 pilot
Ommerli, C; Mirzaagha, J; Ma, C; Bentham, K; Herdman, C (Canada) [35]	2019	Virtual reality flight environments may tax working memory and disrupt prospective memory	20th International Symposium on Aviation Psychology	Considers three aspects (presence, interactivity, and fluency) of users' psychological experiences in virtual reality (VR) and how they might impact prospective memory (PM) (which is the ability to recall or perform an intended thought or action at a future point in time)	47 participants aged 17–71 Flying experience ranged from 2–12,000 h Participants held a mixture of licences from student to ATPL/military
Oberhauser, M; Dreyer, D; Brauning, R; Koglbauer, I (Germany) [36]	2018	What's real about virtual reality flight simulation?	Journal of Aviation Psychology and Applied Human Factors	In this article, a flight simulator based on immersive VR technology is presented: The virtual reality flight simulator (VRFS), which was developed by and is used at Airbus Group Innovations. To assess the fidelity of the system and the bias that is introduced by the virtual environment, the system is compared with a conventional hardware flight simulator	28 participants aged 25–72 The average total flight experience of participants was 2,485 h All participants were qualified pilots although none had any experience with VR

**Table 2** Data extraction table—process and findings

Author/s (base)	Method and concept	Conclusions/outcomes	Key findings that relate to the scoping review question
Pope, T (USA) [11]	Qualitative: multiple data collection methods including telecommunication and in-person interviews with subject matter and data experts. The site visit focussed on collecting production and financial information in addition to interviewing PTN leadership to gain content for the qualitative analysis Cost, production and quality comparison of PTN (VR flight training) with the current UTP system (legacy flight training)	Cost: significant fixed and variable cost savings (financial analysis through accepted accounting practises) Production: potentially significant increases in qualified pilot throughput (statistical analysis and interviews with SMEs) Quality: conclusion limited due to time restrictions and lack of availability of quantitative data (quality comparisons from SMEs (instructors) obtained indicating PTN students to be 'leaps and bounds' ahead of their legacy UPT peers)	The strategic comparison of benefits indicates that PTN is superior from a cost and production standpoint, but further analysis is required to make a comprehensive quality comparison Potential organisational cost savings alone, however, should motivate organisations to investigate VR flight training as an option
Sheets, T; Elmore, M (USA) [23]	Qualitative: a Likert Scale was utilised to gauge subjects' comfort levels An Adaptive Flight Trainer (AFT) was used to conduct a 1-week trial with 40 subjects at Columbus, AFB to test cognitive, kinesthetic and effective learning Participants were trained and evaluated on the USAF 'visual box pattern, to an overhead break' (known as a 'circuit' in civilian aviation parlance) Performance, cognitive load and eye-tracking data from the virtual and physical environments were captured A Likert Scale was utilised to gauge subjects' comfort level with VR and their perceived applicability of the environment to flight training	Performance improvement in altitude and airspeed control was recorded, as well as in procedural task completion in the OFT after 1.5 h of virtual reality learning environment (VRLE) training (Observed indicators and outcomes by USAF instructor pilots and through data capture scripts)	Encouraging results that indicate the possibility that the TLST could reduce costs, be adaptable to an assortment of training requirements, and assist students in synthesising complex principles at a faster rate
Sakib, M; Chaspari, T; Ahn, C; Behzadan, A (USA) [24]	Quantitative: wearable devices were used to collect physiological data from participants Qualitative: mental workload (MWL), stress level, trait and state anxiety, and demographic and daily experience data are also gathered from each participant Flight training, followed by relaxation to establish a baseline Task 1, self-reporting, relaxation Task 2, self-reporting Time of completion and number of collisions were used to measure task performance, calculated as the average time to complete one loop, including the time lost due to collision	Quantifiable evidence based upon physiological data collected by wearable devices, that immersive VR training can be a viable proxy for training drone operators Results of the statistical analysis conducted on different physiological data and self-reports reveal that in most cases, no significant differences are found between VR and OD sessions	Concluded that immersive VR can be a suitable alternative for training and reskilling drone operators and predicting human outcomes in real-world flying conditions

Table 2 (continued)

Author/s (base)	Method and concept	Conclusions/outcomes	Key findings that relate to the scoping review question
Dalladaku, Y; Kelley, J; Lacey, B; Mitchiner, J; Welsh, B; Beigh, M (USA) [25]	Quantitative: comparative correlational research of prior class data Comparison of data from 5 traditional flight training classes against data from all (to date) ATN classes	The original summary statistics analysis supported the VR classes had a lesser standard deviation than the traditional classes (perhaps due to being taught by quality assurance instructors). However, the average score for the check rides almost exactly matches the averages of the historical data. This analysis supports the conclusion that the ATN Programme develops “just as good” aviators	It can be reasonably concluded from the data that the use of VR to supplement flight training does produce aviators of the same quality and competence as pilots trained in a live aircraft
Wilson, J; Scielzo, S; Nair, S; Larson, E (USA) [26]	Quantitative: repeated measures experiment—with each of three flight manoeuvres flown twice Pilot gaze data were collected in a mixed-reality training environment using a physical flight simulator, a virtual reality environment and a gaze-tracking sensor for monitoring eye movements within the virtual space Heatmaps were synthesised from the patterns created by the gaze during flight and analysed by human instructors (Q1) and machine learning (ML) algorithms (Q2) for comparison of results	The performance of the ML multi-task model was comparable to a human instructor for verifying gaze quality. Therefore, it should be possible to deploy this model for applications such as (1) augmenting instructor observations or (2) training pilots to better scan for different manoeuvres automatically in a real-time environment	Can display gaze pattern quality for students or qualified pilots. This can assist pilots (and instructors) in modifying their technique during practise sessions or in-flight
McGowin, G; Xi, Z; Newton, O; Sukthankar, G; Fiore, S; Oden, K (USA) [27]	Quantitative: within-subjects research design, specifically varying the difficulty of the flight scenarios used in the VR environment Participants underwent a training tutorial on the basics of flight, and their knowledge acquisition was assessed They all also engaged with the same set of practise and test flight scenarios, but the presentation order for the scenarios was randomised	This study set out to determine if different forms of knowledge assessment could predict performance in a complex VR flight simulator The study provides evidence that conceptual tests can tap into a deeper form of knowledge integration, and can be more diagnostic of learning efficacy, in this case, predictive of performance for aircraft operations in VR settings	This study extends the knowledge base for both the learning and cognitive sciences by demonstrating how a blend of traditional media with virtual reality can enhance conventional training. It also provides additional insight into the relationship between learning and transfer in virtual reality

**Table 2** (continued)

Author/s (base)	Method and concept	Conclusions/outcomes	Key findings that relate to the scoping review question
Ommerli, C (Canada) [28]	<p>Quantitative: repeated measures experiment with participants completing two test sessions, the first in a traditional flight simulator and the second in a VR flight simulator. Participants were asked to complete a preliminary practise flight 35–45 min flight mission consisting of a four-leg route, which was completed in clear conditions. Participants were provided with a general flight plan and given specific directions</p> <p>At random intervals, the VR simulator was frozen 3 times and the VR HMD was turned off—at this point, situational awareness questions (total 24) following the SAGAT protocol were administered</p>	<p>Findings from this study suggest that telepresence supports SA in VR flight training environments</p> <p>Telepresence experience is highly dependent on a pilot's perception of system interactivity</p> <p>Avoiding events that compromise the continuity and cohesiveness of a pilot's experience of telepresence are essential for ensuring the integrity of the VR flight training environment and enhancing the likelihood of knowledge transfer between simulated and real-world contexts</p>	<p>The results of this research provide meaningful contributions that can be used towards improving the design of VR flight simulators for training and assessment of pilot SA</p>
Lawrynczyk, A (Canada) [12]	<p>Quantitative: repeated measures experiment—participant flew three circuits for each graphics condition</p> <p>Each participant flew 3 circuits of Pendleton Airfield whilst seated in the pilot site of the Cessna 172 flight simulator</p> <p>The research examined the user experience, the cognitive load and the performance metrics in the BADS flight simulator condition against the same flight path and tasks using the VR environment</p>	<p>User experience: no differences in BADS and VR in terms of queasiness, dizziness or disorientation ratings between baseline and first exposure. Queasiness increases in VR after the second exposure</p> <p>Cognitive load: higher subjective ratings of mental workload were reported in the VR condition</p>	<p>This research suggests that although the user experience and performance metrics were comparable (apart from differences in main-taining airspeed), the VR experience likely causes an increased cognitive load on users compared to the BADS</p> <p>Completely replacing traditional flight training in a BADS environment with VR, therefore, could have undesirable side effects</p>
Trinon, H (Belgium) [14]	<p>Mixed methods</p> <p>Quantitative: two-way repeated measures experiment</p> <p>Qualitative: Questionnaire</p> <p>A virtual cockpit was constructed in a virtual environment (VE), with an interactive yoke and four categories of interactive systems: switches, buttons, knobs and levers</p> <p>Two different types of technologies enabling to match the virtual hands to the real physical hands of the user have been implemented: the leap motion and VR gloves</p>	<p>Based on the results of the comparative study on immersion, the technical feasibility of a VR system for pilot training was confirmed</p> <p>Scores computed from the questionnaires showed that the proof of concept provides a VR experience that is more than satisfactory</p>	<p>The proof of concept was tested by technical pilots of ASL Airlines Belgium. Although only a proof of concept which requires some additional adjustments, the pilots stated that its potential for pilot training was real</p> <p>Based on all the results presented, it may be concluded that virtual reality is a potential tool for pilot training in the aviation industry</p>

Table 2 (continued)

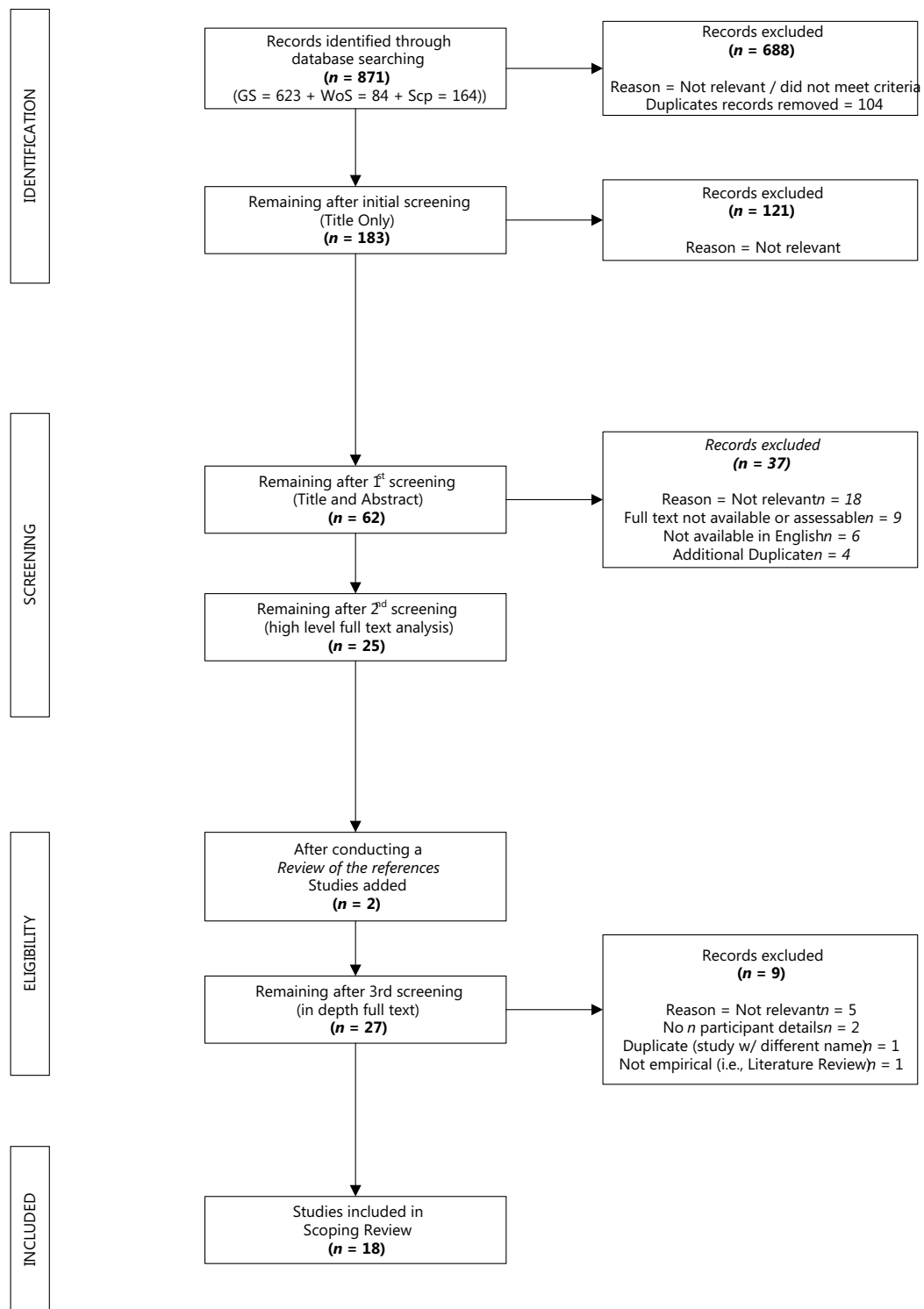
Author/s (base)	Method and concept	Conclusions/outcomes	Key findings that relate to the scoping review question
Pennington, E; Hafer, R; Nistler, E; Seech, T; Tossell, C (USA) [13]	<p>Mixed methods</p> <p>Quantitative: repeated measures experiment</p> <p>Qualitative: VR hand and cybersickness questionnaires</p> <p>Participants were pseudo-randomly assigned to three independent groups with varying degrees of structure</p> <p>(1) High structured, (2) scaffolded and (3) low structured groups</p> <p>The groups represented a spectrum of VR-training curriculum structures ranging from a rigid, linear objective-completion model (akin to traditional flight training) to an unguided, Montessori-like model</p> <p>Hand questionnaire (HQ). It is composed of four items which are rated based on a continuous scale from 0 to 10</p> <p>A cybersickness questionnaire was also filled out by the participants</p>	<p>Initial effectiveness data indicated an increased level of perceived self-efficacy in coordination with increased virtual reality simulator time as well as an accelerated rate of positive transfer to real aircraft from the strictly structured and scaffolded groups</p>	<p>The results of this study do allow for initial recommendations for forthcoming airman-ship training and undergraduate pilot training augmentation efforts across the Department of Defence</p>
Lewis, J Livingston, J (USA) [29]	<p>Qualitative: after-action review (AAR), conducted within one hour of simulated or live flight</p> <p>The VR simulator environment provides multiple types of data analysis, specifically real-time feedback, conducted during simulated flight; after-action review (AAR), conducted within one hour of simulated or live flight; and post-processing, provided days, weeks or months after the fact and entails more computation-intensive analysis</p>	<p>Of the 20 students that started PTN, 13 completed the course, graduating with wings in just half the time of the traditional UPT training method</p> <p>Traditional UPT adheres to a strict schedule whilst PTN allows students to move at their own pace through the curriculum and practical exercises</p> <p>The team believes this student-driven approach will reveal learning patterns that can help inform track selection</p>	<p>On average, PTN students completed their first successful solo flight on their 7th or 8th flight whilst traditional UPT students solo, on average, on their 13th or 14th flight</p> <p>Long term, PTN expects to use its data analysis to inform the development of cognitive models which will be used to predict the success of the trainees in their future training</p> <p>PTN can develop these competency models due to its focus on emerging technologies and data collection</p>
Xi, Z McGowin, G Fiore, S Newton, O Suktanar, G Oden, K (USA) [30]	<p>Mixed methods</p> <p>Quantitative: correlational design</p> <p>Qualitative: questionnaire</p> <p>Training in five sections: aircraft model; aircraft controls; flight manoeuvres; flight instruments; simulator tasks</p> <p>Participants were tested on the concepts they learnt using a questionnaire consisting of ten recall questions, ten descriptive questions and ten conceptual questions</p>	<p>The experiments show that it is feasible to accurately predict student failure on simple flight tasks from visual attention features gathered from the initial flight phase, combined with knowledge mastery features</p> <p>The results affirmatively answer all research questions</p>	<p>The findings in this study provide important stepping stones towards the long-term vision of scalable, automated delivery of flight instruction using off the shelf virtual reality headsets</p>

**Table 2** (continued)

Author/s (base)	Method and concept	Conclusions/outcomes	Key findings that relate to the scoping review question
McCoy-Fisher, C; Mishler, A; Bush, D; Severe-Valsaint, G; Natali, M; Rimer, B (USA) [31]	<p>Mixed methods</p> <p>Quantitative use of Training Integration Management System (TIMS) data from former and current trainees</p> <p>Qualitative collection of the comprehensive questionnaire responses, online or in-person collection of responses to the flight log questionnaire, a wrap-up survey at the end of data collection, in-person focus groups with CNATRA stakeholders</p> <p>Researchers required that all SNAs be given free access to the XR devices. Instructor support was not built into the delivery of the devices; therefore, SNAs did not participate in structured training events with the VR-PTTs. Instead, they engaged in free play or self-guided study sessions with the devices as they desired</p> <p>The MRVS required instructor presence to operate the OFT with which it was integrated, so participants who used the MRVS received traditional OFT instructor guidance during MRVS sessions</p>	<p>(1) Reactions: overall, participants were neutrally favourable to the devices</p> <p>(2) Learning: results may indicate either that COTS VR/MR flight trainers are less valuable for basic flight skills than for more advanced skills</p> <p>(3) Behaviour: conclusions from this section suggest that exposure to VR/MR devices is associated with improved performance</p> <p>4) Results: learning-level data from the T-45C VR/MR devices suggested that they may reduce events needed to meet MIF</p>	<p>Quantitative performance data may support a link between the XR device usage and performance improvement (fewer reflys, marginals, and events to meet MIF). Further, controlled experimental research is needed to clarify the relationship</p> <p>In addition, self-report feedback and focus groups for all four devices indicate that there are perceived benefits provided by XR flight trainers, beyond what is currently available in UTDs and OFTs</p> <p>With noted upgrades, XR systems have the potential to improve performance and can cover the gap in current training</p>
Dymora, P; Kowal, B; Mazurek, M; Romana, S (USA) [32]	<p>Qualitative eight-question survey</p> <p>A sample training application was created in a VR environment to familiarise students with the essential elements of a Socata TB-9 "Tampico" aircraft cockpit</p> <p>The exercise was programmed as a fully immersive VR lesson that replicated the interior of the aircraft, based on photographs, to facilitate the learning of pre-start cockpit procedures</p>	<p>The study draws no supported conclusions and fails to answer the RQ</p>	
Whitson, R (USA) [33]	<p>Quantitative between subjects, quasi-experimental method</p> <p>During the pre-test, participants flew over an urban environment</p> <p>Under the 'simple' post-test landing condition, participants flew over large fields with scattered trees</p>	<p>Results do not appear to support the idea that virtual reality is superior to training with a PC monitor. Once familiarised with the set-up, however, there was some data to suggest that the VR group seems to perform better in the rich textures' environment</p>	

Table 2 (continued)

Author/s (base)	Method and concept	Conclusions/outcomes	Key findings that relate to the scoping review question
Gustafsson, A (Sweden) [34]	Qualitative questionnaires where the moderator first answered some factual questions connected to the participant's performance and then asked the participant to answer some questions connected to the usability attributes The focus of the thesis will be limited to professional, low-fidelity, screen-based flight training simulators and how a VR HMD can be used to complement and improve such a setup	The resolution in the HMD meets the minimum requirements The refresh rate exceeds the minimum requirements The field of view (FoV) is larger than the specified minimum requirements Contemporary VR HMDs did meet the technical requirements of a flight training simulator	The conclusions showed that VR HMDs could be used in some areas of pilot training simulations; however, there are several areas that either needs more research or need to be developed further to be able to fully utilise the capabilities of VR HMDs
Ommerli, C; Mirzaagha, J; Ma, C; Bentham, K; Herdman, C (Canada) [35]	Qualitative questionnaire Randomised auditory PM tasks and tests of working memory using with involved freezing the simulation to ask situational awareness questions	The results suggest that experiences of fluency or intense concentration in VR significantly tap into working memory resources. Content belonging to the VR environment may engage fluency, which could, in turn, divert attention otherwise needed for PM Presence and interactivity were shown to positively influence PM and working memory. Presence had a strong positive effect on both cognitive processes	Fluency: findings are aligned with previous research which suggests that highly vivid sensory experiences in VR create a strain on cognitive resources Presence and interactivity: VR environments with high representational fidelity support enhanced situation awareness, proposing that vivid design facilitates continuity in presence through enhancing the "realism" and "believability" of the experience
Oberhauser, M; Dreyer, D; Braunstingl, R; Koglbauer, I (Germany) [36]	Quantitative: repeated measures experiment The flight task starts with a short taxiing phase from the parking position, a take-off, and a left-hand traffic pattern at an altitude of 2,000 ft	Most participants were able to safely and reliably complete the flight task after a short acclimatisation phase in the virtual environment	The results show that the fidelity of the VRFS is significantly lower compared with the fidelity of a conventional flight simulator, and thus cannot substitute the latter, particularly if the pilot's behaviour and performance are to be as close to reality as possible



In accordance with: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

**Fig. 1** Literature search stages: detailing numbers of sources of evidence screened and included in the review, with reasons for exclusions at each stage

governing authorities may amend this, and reduce the number of flight hours required.

Some form of negative training experience (i.e. functionality issue, simulator sickness) was reported in  $n=2$  quasi-experimental studies, whilst  $n=3$  quasi-experimental studies did not support the idea that xR flight training was better than the alternative legacy option. Distraction, stress and high cognitive load whilst in xR were reported in  $n=3$  (two quasi-experimental and one qualitative questionnaire) studies—although this might not necessarily be considered a negative outcome, with distraction mitigation and desensitisation being options to counter this.

## 5 Discussion

The scoping review identified 18 studies of interest published between 2018 and 2021 that met all inclusion criteria. Of these, the majority had been presented at conferences and subsequently published as conference proceedings, rather than as journal articles. This may have been an artefact of the speed at which technology is advancing in this area (i.e. quickly rendering technology and study data obsolete), making the delays sometimes associated with publishing in academic journals seem less attractive [37, 38]. However, it might also be that some of the studies lacked academic rigour and may not stand up to the stringent peer-review process of high-level journal publication [37]. Another alternative is that the author/s could be continuing their work, including the incorporation of conference feedback, in this area and have, or intend to, submit the finished study to an academic journal for publication in the future [39]. Nevertheless, it is unlikely that these papers will have been subjected to the level of scrutiny normally associated with journal publication; for this reason, any findings should be treated with caution; that said, this is an important finding of the current scoping review.

Most of the included studies were conducted by researchers based in the United States, with 7 of the 18 studies, and most of the participants, originating from the US military. This implies that the US military is currently investing significant time and resources into researching the potential benefits of xR for pilot training and is also reporting optimistic findings through some of their initiatives (i.e. Pilot Training Next). A potential explanation for this is that few, if any, civilian aviation organisations (e.g. flight schools) have the resources and financial capability to match the US military; therefore, in contrast, existing research from these sources appears to be limited in scale and number. In addition, few studies from the civil sector were solely focussed specifically on flight training, instead seeming to concentrate on nuanced areas of training such as learning, human–machine interaction and other human factors.

The majority of both the quantitative and qualitative evidence included in this review supports the potential of xR to be used as an instructional aid in the training of pilots who are currently using traditional flight training methods. The studies suggest that participants who undergo xR flight training are at least as good as those trained using traditional means [11, 24, 25]. There is also evidence to suggest that xR flight training, in concert with traditional flight training, could decrease training time [11, 23, 29, 31], reduce costs [11, 23] and lower the environmental impact of flight training overall [11, 13].

Some studies noted that XR flight training has some noteworthy limitations. VR, in particular, can result in breaks in presence<sup>1,2</sup> (BIP) [40, 41] (i.e. feeling *disconnected*) between the participant and the physical world they occupy (e.g. a VR flight simulator with physical cockpit controls). This BIP can result in restrictions in operation, particularly when the pilot is required to engage with particular aspects of the physical cockpit environment/equipment (e.g., buttons, dials and switches) [12, 36, 41]. MR, which combines images of the physical environment and VE, has the potential to overcome this limitation as it develops [25, 42]. It is also reasonably common to feel the effects of simulator or cybersickness (e.g. cybersickness symptoms include nausea, dizziness, disorientation and headaches and are related to classical motion sickness) [43] during xR exposure, particularly if a participant is susceptible to motion sickness, or new to xR [12, 36], but not always, be overcome with continued exposure over time that may lead to the participant becoming desensitised [43]. It is worth mentioning that conventional simulators as well as real aircraft are also known to cause motion sickness [10].

## 6 Limitations

There were at least three potential limitations identified during this Scoping Review. First, during the search and study identification phase, it is possible that not all of the studies relevant to answering the research question were successfully identified. Second, it is also possible that studies exist that have not, for various reasons (e.g. publication bias), been made publicly available. Third, due to financial constraints, only studies published in English were considered,

<sup>1</sup> Presence (or telepresence as it otherwise known) is an inside-out view of the world where the participant sees and interacts with the VE (e.g. an aircraft cockpit) just as they might if they were physically present. It is the sense one gets of being in the virtual environment (VE).

<sup>2</sup> Breaks in presence (BIP) are moments whilst exposed to a VE that a participant become aware of their real world setting and their sense of presence in the VE becomes disrupted.

which prevented the potential inclusion of six of the identified studies.

## 7 Suggestions for future research

As is evident from the paucity of eligible studies focussing on the use of xR technology and/or VRFS use in flight training (particularly in the civil sector) that there is scope for more research to be undertaken. The greater the amount of data and level of understanding on a topic area such as this will enable those responsible for deciding what future iterations of flight training will entail. Specifically, to assist in achieving this goal, it is suggested that more research should be undertaken in areas such as BIP/disconnect—here the potential benefits of MR's perceived ability to reduce these effects could be further investigated. A comparative study involving civil FTOs could be conducted to assess differences between student pilot groups—some of whom used VRFSs in their training. In concert with a comparative study, a cost–benefit analysis could also be undertaken to compare the costs of differing flight training approaches (i.e. traditional versus VRFS) to gather data that might support the suggestions of cost-saving made in other studies.

## 8 Conclusion of scoping review

The purpose of this scoping review was to (1) answer the research question, (2) provide an overview of the topic and (3) determine the value of conducting a full systematic review.

Despite the aviation industry's proclamations to limit its environmental impact with initiatives such as CORSIA, as well as reducing training time and cost, whilst also increasing pilot throughput, only 18 studies that satisfied the inclusion criteria were identified. This number is low when considering the technological potential, level of innovation and the investment currently being seen in xR technology. From the limited number of studies available, however, there was some evidence to suggest that xR flight simulators could successfully be used in support of traditional flight training.

Overall, this scoping review determined that there is a lack of empirical, peer-reviewed studies in the area of xR flight training. Considering this finding, further investigations into whether xR can satisfactorily deliver an enhancement to traditional flight training methods are required. This is something that could be addressed by academic institutes, particularly those with close ties to commercial aviation. To redress the imbalance that currently exists with military studies, research of an empirical nature involving civil FTOs should be undertaken as a priority, so the results can be better applied to airline and civil aviation. It is suggested

that a longitudinal study involving both instructors and students at a large FTO would in part fulfil this requirement and potentially provide data that could also apply to other commercial FTOs.

It is concluded that, at this moment, not enough high-quality empirical evidence exists to warrant the conducting of a full systematic review.

**Funding** Open Access funding enabled and organized by CAUL and its Member Institutions. The authors did not receive support from any organisation for the submitted work.

## Declarations

**Conflict of interest** All authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The current review was work undertaken for the degree of Masters of Aviation by the first author (GR) [44]. The second author (AG) was the thesis supervisor.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

1. ICAO: ICAO addresses shortage of skilled aviation professionals. <https://www.icao.int/Newsroom/Pages/ICAO-Addresses-Shortage-of-Skilled-Aviation-Professionals.aspx>. Accessed 11 May 21
2. Leontidis, N.: Today, our industry is facing unprecedented challenges. The COVID-19 pandemic is profoundly impacting day to day life, slowing down the global economy, and causing widespread disruption. CAE. <https://www.cae.com/cae-pilot-demand-outlook-2020/#:~:text=As%20air%20travel%20resumes%20progressively,of%20the%20end%20of%202021> (2020). Accessed 11 May 21
3. Boeing: 2020 pilot and technician outlook 2020–2039. [https://www.boeing.com/resources/boeingdotcom/market/assets/downloads/2020\\_PTO\\_PDF\\_Download.pdf](https://www.boeing.com/resources/boeingdotcom/market/assets/downloads/2020_PTO_PDF_Download.pdf) (2020). Accessed 22 Oct 2021
4. Careers.govt.nz: Aeroplane pilot. <https://www.careers.govt.nz/jobs-database/transport-and-logistics/transport-logistics/aeroplane-pilot/how-to-enter-the-job> (2006). Accessed 29 June 2021
5. Bureau of Labour Statistics: Airline and commercial pilots. Retrieved 20/05 from <https://www.bls.gov/ooh/transportation-and-material-moving/airline-and-commercial-pilots.htm#tab-4> (2021). Accessed 22 May 2021
6. Frasca Flight Simulators: How much does a Frasca simulator cost? <https://www.frasca.com/how-much-does-a-frasca-simulator-cost/> (2021). Accessed 4 Oct 2021

7. The Canadian Trade Commissioner: Canadian company soars in training simulator market. <https://tradecommissioner.gc.ca/canadexport/0002526.aspx?lang=eng> (2018). Accessed 21 May 2021
8. Markets & Markets: Augmented and virtual reality (AR, VR) market in aviation by technology (AR, VR), function (training, operations), component (hardware, software), application (on-board, off-board), product, vertical, and region - global forecast to 2025. <https://www.marketsandmarkets.com/Market-Reports/ar-vr-aviation-market-230427667.html> (2018). Accessed 13 May 21
9. Pons, C.: Flying training reimagined as first PTN class graduates. Air Education and Training Command. <https://www.af.mil/News/Article-Display/Article/1594573/flying-training-reimagined-as-first-ptn-class-graduates/> (2018). Accessed 20 May 21
10. Masson, M.: Use and benefits of simulators. <https://www.easa.europa.eu/community/topics/use-and-benefits-simulators> (2021). Accessed 20 May 21
11. Pope, T.: A cost–benefit analysis of Pilot Training Next. Air University, Wright-Patterson Air Force Base (2019)
12. Lawrynczyk, A.: Exploring virtual reality flight training as a viable alternative to traditional simulator flight training. Doctoral dissertation, Carleton University (2018).
13. Pennington, E., Hafer, R., Nistler, E., Seech, T., Tossell, C.: Integration of advanced technology in initial flight training. In: Systems and Information Engineering Design Symposium (SIEDS), University of Virginia, USA (2019)
14. Trinon, H.: Immersive technologies for virtual reality-case study: flight simulator for pilot training. Masters thesis, Liège University, Belgium (2019)
15. ICAO.: Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) ICAO. <https://www.icao.int/environmental-protection/CORSIA/Pages/implementation-elements.aspx> (2021). Accessed 15 June 2021
16. Ahluwalia, R.: Only the rich can afford to be airline pilots due to cost of training, warns industry body. <https://www.independent.co.uk/travel/news-and-advice/airline-pilots-rich-cost-training-poor-students-industry-warn-british-airline-pilots-association-balpa-a7899886.html> (2017). Accessed 19 Oct 2021
17. Robinson, T.: Panel discussion—'the liberalisation of airspace - challenges and opportunities'. In: NZALPA Annual Conference, Auckland (2021)
18. Peters, M., Godfrey, C., McInerney, P., Munn, Z., Tricco, A., Khalil, H.: Scoping reviews—JBI manual for evidence synthesis. <https://wiki.jbi.global/display/MANUAL/Chapter+1+1%3A+Scoping+reviews> (2020). Accessed 20 Jan 21
19. Badampudi, D., Wohlin, C., Petersen, K.: Experiences from using snowballing and database searches in systematic literature studies. In: Proceedings of the 19th International Conference on Evaluation and Assessment in Software Engineering, Nanjing, China (2015). <https://doi.org/10.1145/2745802.2745818>
20. Badampudi, D., Wohlin, C., Petersen, K.: Software component decision-making: in-house, OSS, COTS or outsourcing—a systematic literature review. *J. Syst. Softw.* **121**, 105–124 (2016). <https://doi.org/10.1016/j.jss.2016.07.027>
21. Krishnaratne, S., Littlecott, H., Coenen, M., Geffert, K., Jung-Sievers, C., Kratzer, S., Rabe, J., Rehfuess, E.A., Sell, K., Strahwald, B.: Measures implemented in the school setting to contain the COVID-19 pandemic: a rapid review protocol. *Cochrane Database Syst. Rev.* (2020)
22. JBI Manual for evidence synthesis: Search results. <https://wiki.jbi.global/display/MANUAL/11.3.8.1+Search+results> (2020). Accessed 14 May 2021
23. Sheets, T.H., Elmore, M.P.: Abstract to action: targeted learning system theory applied to adaptive flight training. Air Command and Staff College (2018)
24. Sakib, M., Chaspari, T., Ahn, C., Behzadan, A.: An experimental study of wearable technology and immersive virtual reality for drone operator training. In: 27th International Workshop on Intelligent Computing in Engineering, Berlin, Germany (2020).
25. Dalladaku, Y., Kelley, J., Lacey, B., Mitchiner, J., Welsh, B., Beigh, M.: Assessing the effectiveness of virtual reality in the training of army aviators. In: 2020 Annual General Donald R. Keith Memorial Capstone Conference—Society for Industrial and Systems Engineering, West Point, NY, USA (2020)
26. Wilson, J., Scielzo, S., Nair, S., Larson, E.: Automatic gaze classification for aviators: Using multi-task convolutional networks as a proxy for flight instructor observation. *Int. J. Aviat. Aeronaut. Aerosp.* **7**(3), 7 (2020)
27. McGowin, G., Zerong, Xi, Olivia, B., Newton, G., Stephen, M., Oden, K.: Examining enhanced learning diagnostics in virtual reality flight trainers. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol 64, pp. 1476–1480. SAGE Publications (2020)
28. Ommerli, C.: Examining the effects of perceived telepresence, interactivity, and immersion on pilot situation awareness during a virtual reality flight exercise. Dissertation, Carleton University (2020)
29. Lewis, J., Livingston, J.: Pilot training next: breaking institutional paradigms using student-centred multimodal learning. In: Interservice/Industry Training, Simulation, and Education Conference (IITSEC), Orlando, FL (2018)
30. Xi, Z., Newton, O., McGowin, G., Sukthankar, G., Fiore, S., Oden, K.: Predicting student flight performance with multimodal features. In: International Conference on Social Computing, Behavioral-Cultural Modeling and Prediction and Behavior Representation in Modeling and Simulation, pp. 277–287. Cham: Springer International Publishing (2020)
31. McCoy-Fisher, C., Mishler, A., Bush, D., Severe-Valsaint, G., Natali, M., Riner, B.: Student naval aviation extended reality device capability evaluation. <https://apps.dtic.mil/sti/citations/trecms/AD1103227> (2019). Accessed 20 May 2021
32. Dymora, P., Kowal, B., Mazurek, M., Romana, S.: The effects of Virtual Reality technology application in the aircraft pilot training process. In: IOP Conference Series: Materials Science and Engineering, vol. 1024, no. 1, p. 012099. IOP Publishing (2021)
33. Whitson, R.: Training in a modern age. Masters thesis, Arizona State University (2019)
34. Gustafsson, A.: Use of head mounted virtual reality displays in flight training simulation. Masters thesis. Linköping University (2018)
35. Ommerli, C., Mirzaagha, J., Ma, C., Bentham, K. V., Herdman, C.: Virtual reality flight environments may tax working memory and disrupt prospective memory. In: 20th International Symposium on Aviation Psychology (2019)
36. Oberhauser, M., Dreyer, D., Braunstingl, R., Koglbauer, I.: What's real about virtual reality flight simulation? *Aviat. Psychol. Appl. Hum. Factors* **8**, 22–34 (2018). <https://doi.org/10.1027/2192-0923/a000134>
37. Ernst, M.: Choosing a venue: conference or journal? The University of Washington from <https://homes.cs.washington.edu/~mernst/advice/conferences-vs-journals.html> (2006). Accessed 26 May 2021
38. IEREK.: The difference between a conference paper and a journal paper. <https://www.ierek.com/news/index.php/2018/05/23/difference-conference-paper-journal-paper/#:~:text=First%20thing's%20first%2C%20we%20must,focuses%20on%20a%20cer,tain%20discipline.&text=The%20papers%20submitted%20to%20a,letters%20at%20the%20same%20time.> (2018). Accessed 26 May 21
39. IEEE ComSec. Conference vs journal papers. IEEE ComSoc. <https://www.comsoc.org/publications/journals/ieee-tcom/information-authors/conference-vs-journal-papers> (2017). Accessed 26 May 2021

40. Chung, J., Yoon, H.-J., Gardner, H.J.: Analysis of break in presence during gameplay using a linear mixed model. *ETRI J.* **32**, 687–694 (2021)
41. Laptaned, U., Nichols, S., Wilson, J.: Evaluating situation awareness in different levels of fidelity of synthetic environments: virtual cockpit versus conventional flight simulator. *Hum. Cent. Computing: Cogn. Soc. Ergon. Asp.* **3**, 265–269 (2019)
42. Howard, M.C.: Virtual reality interventions for personal development: a meta-analysis of hardware and software. *Hum. Comput. Interact. Comput. Interact.* **34**(3), 205–239 (2019)
43. McHugh, N.: Measuring and minimizing cybersickness in virtual reality. Masters thesis, University of Canterbury (2019)
44. Ross, G.: Extended reality (xR) flight simulators as an adjunct to traditional flight training methods. Masters thesis, Massey University (2022)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.