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Virtual Reality & Pilot Training: Existing Technologies, Challenges & Opportunities

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Abstract

The introduction of virtual reality (VR) to flying training has recently gained much attention, with numerous VR companies, such as VRM Switzerland and VRpilot, looking to enhance the training process. Such a considerable change to how pilots are trained is a subject that warrants careful consideration. Examining the effect that VR has on learning in other areas gives us an idea of how VR can be suitably applied to flying training. Some of the benefits offered by VR include increased safety, decreased costs, accelerated learning process, and increased environmental sustainability. Nevertheless, some challenges ahead for developers to consider are negative transfer of learning, cybersickness, and failure for users to adopt the technology. In addition to this discussion, existing technologies are presented and compared across a number of areas. Future directions for research and development in VR flying training are considered, highlighting the importance of thorough testing procedures, and shifting research focus to the considerate integration of VR into flying training procedures.

Introduction

The aviation industry has recently seen the introduction of virtual reality (VR) as a training tool for prospective pilots—for example, solutions by Loft Dynamics[1] (https://www.loftdynamics.com/), TACET (https://cineon.training/tacet), and VRpilot (https://vrpilot.aero). This has been driven by rapid developments enabled by a combination of techniques and ideas from the fields of aviation, cognitive psychology, and computer science (e.g., Van Benthem & Herdman, 2021). VR appeals to flight training schools because of its advantages of reduced costs, increased safety, accelerated learning, and environmental sustainability (Jensen & Konradsen, 2018; Lekea et al., 2021). With the increased adoption of

[1] Formerly VRM Switzerland

VR technology to flight training, it is worth pausing to examine current technologies and look at some of the challenges and opportunities in the adoption of VR for flight training. This article reviews existing technologies, discusses challenges and opportunities, and identifies some potential future directions for VR in flight training and, so, is a useful resource for future developers of VR tools for aviation, flight training schools, regulatory bodies, flight instructors, and other relevant stakeholders.

There has been hesitance among the pilot community to adopt new forms of technology that change how pilots operate aircraft, such as behavioral marker systems (Nergård, 2014) and automated devices (McClumpha et al., 1991). However, by collaborating with pilots, the developers of such technologies have taken into consideration pilots' attitudes and adjusted their designs and training procedures accordingly (Rudisill, 1995). For example, the "Third Pilot" approach to flying emphasizes the *partnership* between the aircrew and automation, while maintaining the pilot's autonomy (Cahill et al., 2017). Over the past 62 years, the flight accident rate has dramatically dropped from over 11 fatal accidents per one million flights to 0.04 fatal accidents per one million flights (Airbus, 2022). Although some concerns around automation remain (Sarter & Woods, 2011), the primary contributor to this increased safety is believed to be the integration of new technologies (Airbus, 2022). Increasing safety has been, and continues to be, a priority for any technological advances in the industry.

The introduction of new technologies to pilot *training* procedures have unfolded in a similar vein to aircraft management advancements. Many technological advances have allowed trainee pilots to learn in a safe environment, with reduced risk of harm. For example, the use of computer-based training has allowed flight training schools to teach core competencies, such as situational awareness, from a classroom setting (Bolstad et al., 2010). Arguably, one of the most impactful advancements in flight training has been the use of flight simulators, used as early as the 1920s (Aebersold, 2016). By artificially re-creating aircraft flight, simulators allow trainee pilots to practice flying in all types of weather conditions and experience various flight emergency situations, all in a safe environment. Some additional benefits offered by flight simulators include reduced training costs, increased training effectiveness, and improving the environmental sustainability of flight training (Allerton, 2010). Although there were initially mixed views among flight instructors regarding the use of simulators (Valverde, 1968), stakeholders became more accepting due to reduced costs, increased safety, and the possibility of training large numbers of pilots for team tasks (Aebersold, 2016; Valverde, 1968). By 1979, the majority of pilot training was done in simulators (Aebersold, 2016).

While traditional flight simulators have had a largely positive impact, and simulator use is now seen as an important element of flight training globally (Nowakowski et al., 2014), some notable shortcomings have paved the way for new technologies to further enhance the process. Limitations of traditional flight simulators include predictability (Lekea et al., 2021), expensive operational costs, and reliance on instructor input (Myers et al., 2018). Recently, VR training products have aimed to address some of these shortcomings in training pilots.

It is largely agreed that the idea of VR was first conceived by Ivan Sutherland (1965) who wanted to “make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer’s actions” (Sutherland, 1965, p. 506). A large proportion of the research on VR since its introduction has been aimed towards entertainment and the video-game industry; however, VR only became widely available to, and popular among, consumers in 2016 (Sherman & Craig, 2018). Since then, leading global technology companies, such as Microsoft and Sony, have developed VR products of their own, and the industry is growing rapidly (Alsop, 2022). Even though consumer interest in VR has only intensified recently, the link between Extended Reality (XR)[2] and flying can be traced back as far as 1982. This began when Thomas Furness developed the *Visually Coupled Airborne Systems Simulator* (*VCASS)* which involved the use of a head-mounted display (HMD) along with a flight simulator to provide flight path information (Mazuryk & Gervautz, 1996). A similar application of a more sophisticated XR technology is used to train pilots today. For example, Loft Dynamics combines flight simulators with VR to create training experiences tailored to the individual trainee pilot. They are one of many companies using VR to train pilots (others include VRAI, VRPilot, and Babcock International). Similarly, the United States Air Force now uses VR technology to train pilots in tandem with simulators and cinematic experiences, yielding promising results to date in the form of accelerated learning and increased accessibility for trainees compared to previous training methods (Gonzalez, 2019).

This review will examine how VR can be applied to flight training globally, weighing up the benefits offered by the technology and the challenges facing its adoption. The study and application of VR to pilot training is advancing quickly, but it is important to pause and examine the current literature in this area in order to explore the value that VR can offer the aviation industry. Numerous studies examining VR in aviation have been carried out (e.g., Eschen et al., 2018; Oberhauser & Dreyer, 2017) and reviews have been done in relation to the use of VR in other domains (e.g., Li et al, 2017; Seth et al., 2011). To our knowledge, there has yet to be a review published concerning the use of VR in pilot training. By providing an overview of existing products, this review will serve as a resource for the aviation industry when considering the use of VR in pilot training. Additionally, researchers in this area can use this review to

[2] Extended reality is a collective term including virtual reality, augmented reality, and mixed reality.

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recognize gaps in the literature, challenges ahead, and potential future directions. Likewise, this review serves as a comprehensive resource to future developers of VR in flight training. Using VR to train pilots comes with considerable differences to traditional training procedures (Oh, 2020). Accordingly, proposed changes to the pilot training process need careful consideration, and this review will aid stakeholders in making informed decisions when considering this solution.

The article will first discuss the applicability of VR in flight training in terms of its effect on learning. This will be followed by a summary of existing systems for VR pilot training, examining multiple products currently available. The benefits and challenges of using VR for flight training will also be considered before future directions for this technology are explored. Taking this approach to the review allows for a broad range of topics to be considered.

The Effect of VR on Learning

While VR technology is now being applied to serve a variety of functions, such as improving entertainment and creating artwork (Wexelblat, 2014), using it to enhance learning has also received much research interest in recent years (Radianti et al., 2020). A variety of theories can be used to explain the effect of VR on learning. One such theory is *Experiential Learning Theory* proposed by Kolb and Kolb (2009), which posits that when people get first-hand experience of doing something, it allows them to reflect. These reflections then lead to developments in ways of thinking, and in turn, the skills themselves. Of course, the relevance of this theory to VR is dependent on how close the virtual experience is to the actual experience because the learning is a result of experiencing the task, according to the theory. The *fidelity, presence,* and *immersion* of a VR simulation are important things to consider here. Because there is often confusion around these terms in the cognitive psychology literature (Harris et al., 2020), it is worth pausing to clarify their meaning in relation to VR simulation.

The term fidelity is used to describe the degree to which the virtual environment replicates the real environment, which includes overall appearance as well as the behavior evoked in users (Perfect et al., 2014). Presence relates to “the subjective experience of being in one place or environment, even when one is physically situated in another” (Witmer & Singer, 1998, p. 1). In contrast to the subjectivity of presence, immersion can be viewed as an objective variable, being the technical capability of a technology to lead users to interact with the virtual world as they would interact with the real world (Slater & Sanchez-Vives, 2016). Harris et al. (2020) give a comprehensive outline of how these terms are related to one another and how they collectively impact the learning process. These are important variables to consider when reviewing VR technology, as they can have a considerable impact on the learning experience of the student (Jensen & Kondradsen, 2018).

The value of the learning experience in VR is partially dependent on the degree to which skills used in VR can be applied to real world scenarios. This is captured in *Identical Elements Theory* (Thorndike, 1906) which emphasizes the importance of similarity of stimuli and responses between the learning scenario and the applied scenario. Applying this theory to the use of VR in flight training would suggest that higher fidelity leads to a more positive effect on learning, but research has yielded mixed results in this regard (Myers et al., 2018), and the link between fidelity and training transfer is a continually debated topic in simulation training (Judy, 2018; Reder & Klatzky, 1994). It has been argued that *psychological* fidelity as opposed to *engineering* fidelity (i.e., how well the simulation duplicates the physical environment) strongly influences the transfer of learning (Patrick, 1992). In this way, each element of the simulated

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environment is said to have a “cuing potential" (Cormier & Hagman, 1987), and items of high cuing potential elicit a realistic response from the user. With this in mind, for VR training devices to have a positive impact on the learning experience, the simulated environment must have recognizable cues so that lessons learned in the simulation can be transferred to the aircraft. Recent research has failed to show a significant performance difference between trainee pilots using high fidelity VR flight training and those using 2D simulators (Hight et al., 2022), but it has been suggested that high fidelity tools may be more suitable to later stages of skill acquisition (Reder & Klatzky, 1994).

Although some of the theory may suggest a benefit of high-fidelity VR training devices in terms of transfer of learning, there is a lack of clear evidence that high fidelity leads to learning advantages in flight training (Hight et al., 2022). Despite this, VR is now used in a variety of learning settings among college and school students as part of geography, science, and history curriculums. Studies examining the effect of these applications have revealed an appreciation of VR by both students and teachers, as well as a positive effect on academic results, and higher learning motivation among students (Hursen & Beyoğlu, 2020; Liou & Chang, 2018; Yildirim et al., 2018). VR has also been used in healthcare settings to develop social skills and cognitive skills, such as situational awareness and decision making in high-pressure situations (Bracq et al., 2019). Furthermore, VR is now used to develop perceptual-cognitive skills among athletes (Bird, 2020).

While the effect of VR on learning in flight training needs further research, research on VR in other sectors is encouraging. Given the positive effect of VR on learning motivation in education, and cognitive abilities in healthcare and sport, it seems that VR has the capability to be suitably applied to flight training too. For example, VR may have the potential to aid the development of some of the cognitive and social skills required of a professional pilot, such as situational awareness, communication, leadership, teamwork, problem solving, and decision making, which are all core competencies for pilots (International Air Transport Association, 2021).

Existing Technologies

Flight simulator software, such as Prepar3D (https://prepar3d.com), is now routinely used to train pilots in basic aviation (Gonzalez, 2019). Simulators allow trainee pilots to master manual flying skills by practicing steady and accurate maneuvers and dealing with non-standard situations (Socha et al., 2016). Modern flight simulator software includes features, such as accurate aircraft dynamics, detailed weather simulation, realistic ground control, and other air traffic and can now run in an immersive VR environment. Additionally, it is possible to deliver simulation experiences, both VR and non-VR, in cheaper desktop simulation environments using non-specialized hardware, rather than in expensive full motion simulators (Oberhauser & Dreyer, 2017). Although research has been ongoing in VR flight training, the integration of VR into flight training curriculums has only been approved recently by the European Union Aviation Safety Agency (EASA). In fact, the first training device utilizing VR that allows time to be credited towards flight training was only approved in 2021 (Loft Dynamics, 2021). Table 1 shows a list of notable examples of flight training products utilizing VR currently in use. We describe four of these in detail to illustrate the current state of available technology and demonstrate the range of products.

Airbus H125 Flight Simulator Training Device

This product was developed by Loft Dynamics, one of the leading companies in VR pilot training. Beginning in 1998 with a train simulator, the company today specializes in helicopter

VR simulation (Loft Dynamics, 2022). The company produces several simulator-like machines that use a VR HMD and have replicated various helicopter models. In May 2022, along with Airbus Helicopters, the company launched the H125 flight simulator training device (FSTD), which represents an Airbus AS350 B3e. The company places a large emphasis on providing an immersive experience for its users, with the device using a full-scale cockpit replica and a motion platform, coupled with a VR HMD to accurately represent the physical feeling of flying. The product also uses a 'Human Pose Tracking System,' which uses multiple cameras to produce an accurate image of the users' own hands as they interact with the flight controls. This provides an advantage over other products that use gloves or hand-held controls to interact with their environment. While a strength of this company's products is the level of immersion provided to the user, the extra hardware required to achieve this makes accessibility an issue, not lending itself to remote learning. One major advantage of this product is its EASA qualification, allowing hours spent by trainees to be credited towards qualification. The product has recently been introduced in the United States, with plans to qualify the device under Federal Aviation Administration regulations (Vertical Mag, 2022). Loft Dynamics recognize cost, environmental sustainability, and safety as key advantages over traditional simulators. However, there doesn't appear to be empirical evidence highlighted by the company to demonstrate the product's purported effect on learning.

Training Air Crew Competency using Eye Tracking

Another emerging VR flight training product is Training Air Crew Competency using Eye Tracking (TACET) (Cineon Training, n.d.), launched in 2022. TACET is a training application that is used on the Pico Neo 3 Eye VR headset. Built on the back of a strong evidence base (Harris et al., 2022), this product uses eye-tracking technology via a VR HMD to automatically assess a pilot's abilities. Eye-tracking data can be analyzed to produce scores on various non-technical flying skills such as situational awareness, workload management, and decision making. Since these are usually difficult skills for instructors to assess manually, this product aims to have a positive impact on the current learning process for the student and instructor. The product also allows video playback of the flight, enabling the instructor to pause and play specific instances when giving feedback. Research has shown the value of the product in assessing expertise using eye-tracking (Harris et al., 2022) and positive impressions from pilots have been reported (Cineon Training, n.d.). Compared to traditional simulators, the product is marketed as less expensive and more accessible.

EMPACT

EMPACT is a learning platform that allows companies to create and manage XR pilot training. The Varjo XR-3 headset is used in conjunction with the platform. Created by HTX Labs, the U.S. Air Force use this platform to train pilots as part of the Pilot Training Next (PTN) program (Gonzalez, 2019). Apart from the obvious benefits of XR training, an extra advantage of this product is the ability for multiple students to practice together, at the same time in the same virtual world, making formation practice possible and developing situational awareness skills. EMPACT also uses artificial intelligence to create an individualized program for the student. Initial findings from the PTN program indicated that pilot training can be accelerated using XR training, with a high quality of pilot still being produced (Gonzalez, 2019). In fact, for the first time in U.S. Air Force history, two graduates of this program led a mission sortie as commander and co-pilot in late 2020 (Charles, 2021). Despite positive reports from the program to date, there doesn't appear to be an abundance of research evidence supporting the supposed advantage in training quality.

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V360E Cockpit Procedure Trainer

V360E is a flight training tool that allows users to train remotely, without the need for fixed motion simulator equipment. The product can be easily connected to the user's mobile device regardless of their location. The increased accessibility of this product is one reason it appeals to flight training schools. For example, Babcock International started using this product among its pilots for this reason (V360E, 2020). The product gives instructors the option of using pre-made training programs or adding their own content to training and allows them to monitor their students' progress. Researching the effects of the product in a Danish pilot academy, the company reported more confident students, more effective study time, and more effective simulator sessions following the use of this product in comparison to traditional flight training methods (V360E, 2020).

Table 1

Current VR Flight Training Products

Product Name	Country	Estimated original launch date	Remote training capabilities	Haptic feedback[a]	Eye tracking	Stress Monitoring	Additional Equipment Required[b]	Link to website
Aviar	Netherlands	2019	Yes	No	No	No	PC, VR HMD	https://aviar.nl
FlightDeck ToGo / Visionary Training Resources	United States of America	2022	Yes	No	Yes	No	None	https://www.vtrvr.com
CAE Sprint	Canada	2019	No	Yes	Yes	No	None	https://www.cae.com/defense-security/what-we-do/training-systems/cae-sprint/
EMPACT	United States of America	2018	No	Yes	No	No	PC, Varjo XR-3	https://www.htxlabs.com/simulations/military
TACET (Training AirCrew Competency using Eye Tracking)	United Kingdom	2022	Yes	No	Yes	Yes	PC	https://cineon.training/tacet

Product Name	**Country**	**Estimated original launch date**	**Remote training capabilities**	**Haptic feedback[a]**	**Eye tracking**	**Stress Monitoring**	**Additional Equipment Required[b]**	**Link to website**
V360E Cockpit Procedure Trainer	Denmark	N/A	Yes	No	No	No	Mobile device, PC	https://home.v360e.com/aviation
Airbus H125 Flight Simulator Training Device	Switzerland	2017	No	Yes	No	No	PC	https://www.loftdynamics.com/
VRflow	Denmark	2019	Yes	Yes	Yes	No	PC	https://vrpilot.aero/vrflow/

Note. This is a representative rather than an exhaustive list of VR flight training products currently on the market. The information provided in this table is based on the available information on the product's respective websites.

a Includes any physical representation of the cockpit, for example rudder pedals and yoke.

b Includes any equipment needed in addition to the hardware/software provided by the company.

Benefits

The recent research and development of VR pilot training technology suggests a number of benefits from this approach. It is worth pausing to consider some of the evidence-based benefits offered by VR pilot training. Primarily, VR allows for reduced costs and improved safety, but additional reported benefits include having a positive impact on the pilot training process and projected higher pass rates in flight schools (McLean et al., 2016).

Using VR in pilot training can positively impact training in several ways. VR uses stereoscopic screens that present two slightly different images of the same scene, allowing the user to perceive distance more accurately than when using a single screen in a typical fixed-base simulator (Tovée, 1996). Depth perception is seen as a vital part of flying, especially in military aviation where pilots must be able to accurately judge distances to complete formation flying, aerial refueling, and obstacle avoidance (Winterbottom et al., 2014). Additionally, many VR simulators allow 360° vision for the pilot (e.g., Loft Dynamics products), compared to a maximum of only 180° in most flight simulators. This enables pilots to perform crucial lookout procedures and maintain high levels of situational awareness, a core competency of a professional pilot (International Air Transport Association, 2021). In addition to situational awareness, VR pilot training targets other cognitive skills that are critical in the development of pilots, including problem solving, decision making, and workload management (Harris et al., 2022).

Yet another benefit of using VR in pilot training is the potential use of the data that can be collected. Coupling simulated flight training with extensive data capture and analysis offers the opportunity to radically change how pilots are trained and assessed. While a pilot is flying a training scenario within a simulated environment, massive amounts of data can be captured on their every move – from where they are looking within the simulated world to every control input they provide. This ability to capture data is a significant advantage of training in a simulated environment over real flying. By analyzing the data captured during simulator flying, the performance of the trainee pilot can be assessed objectively, feedback can be provided, and training recommendations can be made. While there is some early work in this regard (Jasra et al., 2018; Harris et al., 2022), this is not something that is incorporated into all VR flight training solutions but could prove beneficial. While instructor supervision is a requirement in the use of many flight simulators to provide guidance, instruction, feedback, and control the occurrence of various weather conditions and emergency situations (Myers et al., 2018); VR pilot training can cater to independent learning by providing trainees with these elements automatically (e.g., TACET, EMPACT, CAE Sprint). In addition to less supervision pressure put on instructors, the objectivity of the data provided enables instructors to identify key areas of improvement in their trainees and target those areas in their training. It is worth noting that these features are not available across all VR flight training products.

Safety is a substantial benefit offered by VR pilot training. Using VR allows training programs to expose trainees to emergency situations in the cockpit without endangering the trainees (Lekea et al., 2021). VR can be used to induce stress in trainees and better prepare them for high-pressure situations (Stinson & Bowman, 2014), all in a safe manner. Due to increased ability to practice high-pressure and dangerous situations, increased emphasis on developing cognitive skills, and potential for more objective feedback processes, VR pilot training can positively impact the overall training process. While preliminary results (e.g., Dymora et al., 2021), including the Pilot Training Next program in the U.S. Air Force (Gonzalez, 2019), are positive and the effectiveness of VR in other training scenarios (such as education and healthcare) has been backed by research (Butt et al., 2020), there is more research needed on the effectiveness of VR pilot training.

The potential for reduced costs in flight training is a noteworthy benefit. While VR technology can be expensive to purchase initially, the more students that use it, the more cost-effective it becomes (Fleming, 2020). In comparison to most flight simulators, VR training is cheaper to implement, and the cost is becoming more accessible as the technology develops (Yavrucuk et al., 2011; Ziakkas et al., 2023). This is partly due to the materials needed. Most flight simulators use the same aircraft parts as the actual cockpit itself. Depending on the fidelity of the VR device, much of this can be represented virtually, reducing costs. Even larger VR training devices such as those produced by Loft Dynamics are still cheaper than most traditional flight simulators. Additionally, some VR training devices have the capacity to present various types of aircraft using the one HMD. Less need for specialized hardware can also contribute to a lower overall cost. In addition to all the benefits offered over traditional flight simulators, VR flight training has the potential to save money on fuel costs that accompany live practice flights (Lawrynczyk, 2018), in a similar way to traditional flight simulators. Reduced fuel usage also contributes positively to the environmental sustainability of flight training. Because VR pilot training can have a positive impact on the training process for trainees, companies developing VR training products claim that it has the capacity to allow more students to pass through training successfully. Given the substantial costs associated with pilot training (Aviationfly, 2022), having a higher pass rate among their students would present a greater return on investment for flight schools. Although VR companies claim higher pass rates as a benefit of VR pilot training, there is a lack of research comparing pass rates between traditional training methods and VR training. VR pilot training also has the potential to address pilot shortages (Van

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Benthem & Herdman, 2021), which is an ongoing global issue (Caraway, 2020). Because VR can improve course pass rates and graduate pilots faster (Gonzalez, 2019), it allows vacancies to be filled sooner. Furthermore, an added benefit of VR pilot training is the eagerness of the flight training community to adopt this technology (Zhang, 2022).

Challenges

In spite of the many benefits offered by VR flight training, there are some challenges that may affect its uptake. If VR flight training is to lead to a positive transfer of learning, the simulated environment must replicate the most relevant cues from the real environment (Patrick, 1992). While VR offers many advantages over traditional simulators in terms of fidelity (e.g., 360° vision and depth perception), there still remain elements of the virtual environment that do not accurately represent the actual environment. Pilots flying actual aircraft are exposed to many stressors that may induce a physiological response and affect their performance (Summerfield et al., 2018). These are not reproduced in typical VR simulators and there is a risk that VR may not elicit stress levels in pilots that are representative of a live flight (Wilson & Soranzo, 2015). This gap between the virtual and real world may make it harder for trainees to adapt to stress levels in a live flight. If VR fails to elicit a realistic stress response within trainees, it may be more suitable to training skill mastery as opposed to performing at high stress levels. Further research is required to identify the specific areas of flight training that VR can benefit.

Oh (2020) reported that users of VR pilot training found the electronic cockpit system difficult to use and that conventional simulators were easier to use. The lack of realistic haptic input in VR may contribute to this difficulty and widen the gap between the virtual and actual environments (Levac et al., 2019). Due to these discrepancies between the training and performance environments, there is the potential for "negative transfer" of learning (Perkins &

Salomon, 1992, p. 3). This may manifest itself in bad habits being developed among trainee pilots. Overall, there is a scarcity of specific research investigating the transferability of skills from a virtual to a real environment in flight training, and this warrants further research (Levac et al., 2019).

Another noteworthy challenge for VR training solutions is the health effects of VR. VR has previously been shown to induce feelings of queasiness, dizziness, and disorientation, or *cybersickness* (Viziano et al., 2019). Cybersickness is thought to result from an imbalance between sensory experiences and expectations (Dymora et al., 2021). Other symptoms associated with VR usage include eye fatigue, foggy vision, abdominal pain, hallucinations, and digestive issues (Jerdan et al., 2018; Stauffert et al., 2020). Research on VR in flight training has taken this into consideration and aimed to prevent these symptoms from occurring in the first place by limiting the amount of time spent in VR and including regular breaks (Van Benthem & Herdman, 2021), but this is a persisting challenge (Farmani & Teather, 2020) that needs to be continually considered as there is still much to learn about how to deal with it (Davis et al., 2014). Even when users follow guidelines and best practices, there is still a risk of cybersickness, which can be a major barrier for acceptance (Ramaseri Chandra et al., 2022). Understanding the health effects of VR usage and how to navigate this issue is essential to the safety of users and ultimately the degree to which the technology is accepted and used.

Arguably, the most important challenge to consider for VR pilot training is the willingness of stakeholders to adopt the technology. This includes instructors, trainees, flight training schools, national funding bodies and aviation organizations. The aforementioned challenges may contribute to a reluctance among stakeholders to accept the solution. Even if the risks of negative transfer of learning and health effects are accounted for, fear of their occurrence may lead to reluctance to use VR technology in flight training. For example, fear of negative transfer can discourage flight instructors from adopting new technology (Marques et al., 2022). Such a fundamental change in the pilot training process will require new training for instructors to complete and may even alter assessment methods used, placing more reliance on automation than professional judgment, a topic that has previously proved controversial (Nergård, 2014). How VR is used to enhance the training process as opposed to replacing the current process may be an important factor in its uptake, or lack thereof. Additionally, even if VR flight training products are readily available to, and accepted by, students and instructors but hours spent using this technology cannot be credited towards training, the technology may fail to be used. For VR flight training to be successful, regulatory bodies must see the value in the technology and adjust training regulations, accordingly, as has been seen with Loft Dynamics and EASA (Loft Dynamics, 2021).

Future Directions

In the continually evolving field of VR, new ideas are constantly emerging with more basic forms of the technology becoming more readily available (Anthes et al., 2016). With the rapid growth of VR in pilot training, it is important not to bypass the appropriate testing and research needed before implementing the solution in the flight training process. Given the numerous benefits that VR offers, it is clearly worthy of further research. Many recent studies in this area have stressed the need for appropriate testing of solutions (Harris et al., 2020) and further research into the exact effect VR has on trainee pilots (Fussell & Truong, 2020; Hight et al., 2022; Van Weelden et al., 2021). Similarly, there is a lack of studies comparing VR flight training devices to traditional simulators in terms of pass rates and effect on learning. More research needs to be done to identify the specific areas of a simulation environment than can heighten psychological fidelity. Aside from fidelity, it is also important to consider the design of learning platforms using VR to ensure that they cater to optimal learning. One specific area worthy of more research that was already mentioned is the use of VR to train cognitive skills in pilots. Although there are initial uses of eye-tracking technology to do this (e.g. Harris et al., 2022), it is an application of the technology that is still in its infancy.

There have been numerous additional uses for VR in aviation suggested that warrant further research. For example, Van Benthem and Herdman (2021) have investigated the use of VR to re-train pilots who have missed flying time through Covid-19, as well as using it to screen pilots for cognitive deficiencies. Updegrove and Jafer (2017) have suggested using VR in Air Traffic Control training, a highly pressurized job, which may benefit from VR training. Similarly, aircraft maintenance has been another suggested area of application for VR in aviation having received more research attention (Matos et al., 2019). Voice recognition could be a beneficial addition to VR flight training but presents some issues such as background noise affecting usability and subsequent poor persistence with VR training (Severe-Valsaint et al., 2022). However, if employed effectively, this could provide a realistic ATC element to VR flight training devices.

One subject that has yet to be brought into the VR flight training conversation is performance psychology. Performance psychology research into how VR can be used in areas, such as performance anxiety, stress management, and confidence, can be adapted to the field of aviation. Notably, a recent study demonstrated how VR can be used to induce performance anxiety in athletes (Kelly et al., 2022). Using VR to investigate trainees' responses to pressure coupled with mental skills training is an avenue worth exploring. This approach is yet to be employed (or researched) in aviation to the best of our knowledge but has previously been used

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to teach stress management and coping strategies in the military (Pallavicini et al., 2016). These are skills that would likely prove beneficial for trainee pilots.

While there are some innovative uses for VR in aviation currently being suggested as noted above, it is equally (if not more) valuable to investigate the logistics of the ideas. In the "Existing Technologies” section of this paper, we presented multiple competing VR solutions. As Jensen and Konradsen (2018) noted, a pragmatic approach to VR training solutions may be more beneficial than an idealistic approach that focuses on innovation more so than integration. For example, for VR to be successfully adopted long-term, it must adhere to aviation regulations and have an established role in flight training curricula globally. As seen with the introduction of conventional flight training simulators, this can be a long and arduous process (Ebbage, 2004). Perhaps researchers should shift their attention to how current VR solutions fit into the flight training process and how we can integrate a beneficial technology into flight training globally long-term.

Conclusion

Despite the numerous research studies looking at VR flight training (Harris et al., 2022; Lekea et al., 2021; Myers et al., 2018) and the range of products available (e.g., EMPACT, CAE Sprint, Aviar), there has yet to be a review published examining the use of VR in flight training. This article aimed to address this gap in the literature by providing a resource to future developers and researchers in this area. Looking at how VR can impact the learning process in other industries should provide confidence that VR can be applied to flight training, but further research is needed to make clear how it can affect the learning process among pilots. This article can serve as a reliable source of information for developers and users of this technology, as well as aviation researchers. The benefits that VR has to offer the aviation industry are apparent. By discussing challenges ahead and potential future directions, it allows this technology to progress in a well-informed manner.

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