frontiers in Virtual Reality

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Enhancing pilot training with virtual reality: evaluating skill acquisition and student perceptions

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Virtual Reality (VR) has emerged as a promising tool for pilot training. Some aviation companies have started incorporating VR into their training programs, but more research is needed to prove its efficiency as a learning tool. This study has two aims: to determine to what extent the use of VR improves pilot learning skills before a student's first real flight, and to explore the vision of the students and instructors. A quasi-experimental design is implemented, with participants divided into a control group (traditional classroom training) and an experimental group (VR-based training), along with a focus group to explore the second objective. The results indicate that students who trained with VR achieved significantly higher scores in their first real flight compared to the control group, supporting the hypothesis that VR enhances practical skill acquisition. However, VR training was less effective in improving theoretical knowledge, as the traditional classroom group showed greater gains in post-test scores, a finding that can be explained by the Cognitive Load Theory. Qualitative data revealed that students and instructors recognized the potential of VR for pilot training, highlighting benefits such as increased immersion, spatial awareness, and confidence. Despite these advantages, limitations such as the lack of physical feedback, occasional technical issues, and minor ergonomic challenges were noted. Findings suggest that while VR cannot replace real-world flight experience, it serves as a valuable supplementary tool for enhancing flight skills and procedural training. Future research should explore long-term retention of VR-trained skills, refine VR learning experiences to better support theoretical knowledge, and examine its integration with traditional training programs.

KEYWORDS
aviation education, flight simulation, pilot training, skill acquisition, virtual reality

1 Introduction

To obtain a commercial pilot license, all aspiring pilots must complete both real flight hours and simulated flight hours. The demand for airline pilots is increasing, projections for 2041 suggest this number could rise to around 600,000 to meet industry needs (Airbus, 2022; Boeing, 2022). This growing demand is creating a significant challenge in training capacity, particularly in the availability of flight simulation resources. Simulation has been pedagogically explored for decades, with sustained efforts to make flight simulators as realistic as possible (Caro, 1973). Nowadays, virtual reality (VR) technologies could play a crucial role in addressing this challenge by providing accessible and cost-effective simulation options to supplement traditional training methods.

VR is not a new tool, but its implementation in the education field was hindered by high costs until 2013. Then, the company Oculus Rift revolutionised the industry by making VR technology more affordable, thereby enabling its viability in education and training. Additionally, this technology has advanced considerably improving its capabilities (Jensen and Konradsen, 2018). From there, VR has proven to be an effective learning tool in diverse disciplines, mainly health, sciences and engineering (Kavanagh et al., 2017). However, fewer investigations have studied its application in the aviation field (Ross and Gilbey, 2023).

In here, we want to introduce our VR flight simulator during the initial stage of flight instruction in a university degree for professional pilots. Concretely, in second course student pilots just before their first real flight. Our objective is to test whether a Virtual Reality Flight Simulator (VRFS) improves the performance in the first real flight.

Virtual reality (VR) has demonstrated significant potential in enhancing learning outcomes in higher education by providing immersive and interactive experiences (Slavova and Mu, 2018; Vats and Joshi, 2024). Systematic reviews and meta-analyses have highlighted various benefits of VR, such as improved student engagement and understanding of complex concepts, facilitated through games, simulations, and virtual worlds (Merchant et al., 2014; Young et al., 2020; Xiaoning et al., 2024). These applications are predominantly seen in science, engineering, and medical fields, with limited implementation in humanities and social sciences (Ding and Li, 2022).

VR's ability to enhance student engagement, foster immersive learning experiences, and improve knowledge retention is influenced by factors such as feedback type, individual vs. group gameplay, and treatment session duration (Merchant et al., 2014; Slavova and Mu, 2018; Vats and Joshi, 2024). However, challenges remain, such as the need for more portable devices and better pre-class training for students (Ding and Li, 2022). Researchers have proposed various guidelines and frameworks, including empathy mapping and heuristic principles for lesson planning, to support effective VR integration in higher education (Young et al., 2020). Also, pre-training before using VR has been found to have a positive effect on knowledge and transfer (Meyer et al., 2019). As VR technology evolves, its potential to transform teaching methods and offer diverse learning opportunities becomes increasingly evident (Xiaoning et al., 2024).

Studies show VR's suitability for acquiring practical skills (Kavanagh et al., 2017; Jensen and Konradsen, 2018). The immersive nature of VR facilitates active learning and concept assimilation. For instance, Chen et al. (2020) found that students using VR exhibited improved hands-on abilities and learning performances. On the other hand, studies suggest that VR is not more efficient than traditional learning in terms of knowledge retention, but significantly similar (Jensen and Konradsen, 2018; Sichterman et al., 2023; Šikl et al., 2024).

Moreover, the Cognitive Affective Model of Immersive Learning (CAMIL) explains that immersive VR influences learning through key psychological mechanisms such as presence (the feeling of *being there*) and agency (the sense of control). These factors can enhance learning by increasing attention, motivation, self-efficacy, and embodied cognition, leading to deeper engagement and improved understanding (De Witte et al., 2026; Makransky and Petersen, 2021). However, immersive VR can also hinder learning when it introduces excessive cognitive load, distractions, or unguided exploration, which may overwhelm learners and reduce effective processing (Makransky and Petersen, 2021).

Some concerns have been raised about using VR in education, such as cybersickness (Jensen and Konradsen, 2018), the challenge of introducing new technologies for educators (Bower et al., 2020), and distractions from the main learning task (Mayer et al., 2023). Such distractions may increase extraneous cognitive load, using part of the working memory and reducing the student's capacity to process information and store it in long-term memory, which may reduce the effectiveness of VR as a learning tool (Sweller et al., 2011).

Finally, Rebelo et al. (2012) identified three primary advantages of virtual environments for education and research:

1. *Availability:* Teachers and researchers can create customized environments, replicable across various locations and scenarios.
2. *Safety:* Students can learn specific skills in controlled hazardous scenarios safely. Researchers can manipulate factors affecting participants' performance, such as mental workload or induced stress, which can be precisely defined and replicated.
3. *Data Provision:* The reproducibility of simulated experiences allows researchers to gather accurate and valid data, often inaccessible in real-life settings.

In aviation training, VR technology offers immersive and interactive experiences that can significantly enhance pilot training and safety procedures (Cross J. I. et al., 2023; Ross and Gilbey, 2023; Shui et al., 2023). Moreover, VR technology's cost-effectiveness, accessibility, and sustainability present advantages over traditional simulators (Ziakkas et al., 2023). FSTDs are certified simulators widely used in advanced phases of pilot training, but their high cost and regulatory requirements make them impractical for early stages. Therefore, studies were performed to validate its efficacy compared to traditional Flight Simulator Training Devices (FSTD) (Oberhauser and Dreyer, 2017; van Weelden et al., 2021), where arousal and workload was found higher in students piloting a FSTD (Vallès-Català and Guerrero, 2025). These studies highlight that VR systems still present limitations regarding the interaction with cockpit instruments and the tactile feedback required for complex procedures. For this reason, VR is most suitable for initial phases of pilot training, where the focus is on basic familiarization and procedural understanding, and where FSTDs are rarely used due to their prohibitive cost and certification constraints.

Studies by Guthridge and Clinton-Lisell (2023) and Hight et al. (2022) have demonstrated that VR-trained participants achieve learning outcomes comparable to those using traditional simulators, often outperforming control groups. VR has been studied in military pilot training, where an increased level of perceived self-efficacy has been found (Pennington et al., 2019). Additionally, given the critical role of spatial visualization in pilot training, VR has been effectively used to administer the mental rotation test, a key predictor of pilots' spatial reasoning skills (Zhang et al., 2023). Moreover, VR's personalized capabilities make it

particularly well-suited for procedural training with adaptive feedback, as required in pilot instruction (Aguilar Reyes et al., 2023).

Nevertheless, challenges such as adapting learning materials to technical requirements and optimizing exposure duration to prevent physiological issues remain (Dymora et al., 2021).

VR is a promising tool for aviation training and many flight schools are adopting this technology. However, studies have provided only limited evidence of the effectiveness of learning in a VRFS and the transfer of skills to real-world settings and further studies are needed (Cross J. et al., 2023; Ross and Gilbey, 2023; Shui et al., 2023).

In this context, the overall objectives of this study were:

GO1- to determine to what extent the use of VR improves pilot learning skills.

GO2- to explore the vision of the students and instructors.

Regarding these objectives, the following two hypotheses were posed:

Hypothesis 1: The students in the VC group attain better results.

Hypothesis 2: The participants recognize the potential and practicality of using virtual reality for developing pilot skills.

2 Materials and methods

For this study, 30 student pilots volunteered to participate in the experiment, with an age range of 18–21. The participants are enrolled in the Degree in Commercial Aviation Pilot and Air Operations at anonymised university, a university specializing in pilot training. The VR component is intended to be part of their second coursework, preparing them for their first real flight with the Diamond DA20 aircraft. Among the final participants, only three were female, accounting for 10% of the total, a similar percentage to the current active female pilots (CAPA - Centre for Aviation, 2023). All of them provided written informed consent, in accordance with the guidelines approved by the ethical committee of the anonymised university under code CEIPSA-2023-PR-0029. Finally, three participants decided to withdraw from the study, and their data was not included in the analysis.

2.1 Materials

In this study, we employed the following components to create a VR flight simulator (see Figure 1) like a previous study (Vallès-Català and Guerrero, 2025), which, though not certified for official flight training, can be used as a supplementary tool:

1. Oculus Quest 3: A VR headset with a 110 ± 4-degree horizontal and 93 ± 5.1-degree vertical field of view, and a 120 Hz refresh rate. To prevent connectivity issues, it was connected to the PC via a cable. Previous studies have also used similar Oculus devices in VR research (Estupiñán et al., 2014; Egan et al., 2016; Alves Fernandes et al., 2016; Kakkos et al., 2019; Kritikos et al., 2019).
2. PC: A Windows 10 system with an Intel Core i7-9700K processor and GeForce RTX 3080 10 GB graphics card. The direct connection between the headset and PC ensured a low latency of 10–30 m, which supports immersive experiences and reduces cybersickness (Oberhauser and Dreyer, 2017).
3. Microsoft Flight Simulator 2020 Deluxe Edition: This software was chosen for its realistic visuals and flight dynamics, adequate for simulation and research (Vallès-Català and Guerrero, 2025). Featuring the DA20-C1 aircraft from SimSolutions via the iniBuilds platform, along with the LERS airport. Both closely resemble the participants' real-world flight training environments. We configured the software to be as minimalistic as possible, reducing visual aids during the VR flight in order to make the experience more realistic and to reduce distractions and extraneous cognitive load (Sweller et al., 2011).
4. Flight Controls: The VPC WarBRD Grip joystick with a VPC MongoosT-50CM2 base was used to control the aircraft's roll and pitch, while the Logitech G Flight Simulator Throttle Quadrant managed throttle and flaps. The Oculus Touch Controllers were only used for pointing instruments during the pre-flight checklist. Additionally, Logitech flight rudder pedals were used to control yaw via foot input.

2.2 Experimental design

This study is based on a quasi-experimental design exploring the effect of the type of training environment (virtual reality vs. control) on the improvement of learning skills and the participants' view, by using post-test scores, student marks after real flight, observations by instructors, and interview data from both students and instructors.

All pilot students must complete a specialized course focused on the DA20 aircraft, the model they would later use during their flight training. Therefore, all participants had received prior theoretical instruction on the DA20 aircraft before the study intervention (VR or control). After successfully finishing the course, participants were ranked by their final marks. To ensure balanced control and experimental groups, we applied a blocked randomization procedure: participants were assigned alternately to control and experimental groups based on their ranked position. Before allocation, a Python script using the random library randomly determined whether odd positions would correspond to the control group or the experimental group. In this study, odd positions were assigned to the control group.

As seen in Figure 2, participants were divided in two groups. Those in the control group received a traditional, instructor-led classroom session lasting around 45 min. During this session, a flight instructor provided an overview of the DA20 aircraft's instrumentation and standard flight procedures. In contrast, participants in the experimental group completed a 45-min VR session, where a flight instructor faithfully simulated their upcoming real flight.

Additionally, the control group had a separate 45-min VR flight simulation session after their real flight session, which is not considered for the study but provides an opportunity for all participants to experience VR, not creating a comparative disadvantage for the control group.

Although all participants completed the DA20 course at the same time, their first real flights were scheduled on different dates over the following months. In this study, efforts were made to ensure



FIGURE 1
Virtual Reality Flight Simulator (VRFS) setup. The VRFS is based on a Oculus Quest 3 head mounted device, connected to a high-performance PC computer to enable a fluent and realistic experience. To avoid the use of the Oculus Touch Controllers, to enhance the flight simulation, several flight instruments are used: VIRPIL joystick, Logitech throttle and Logitech flight rudder pedals.

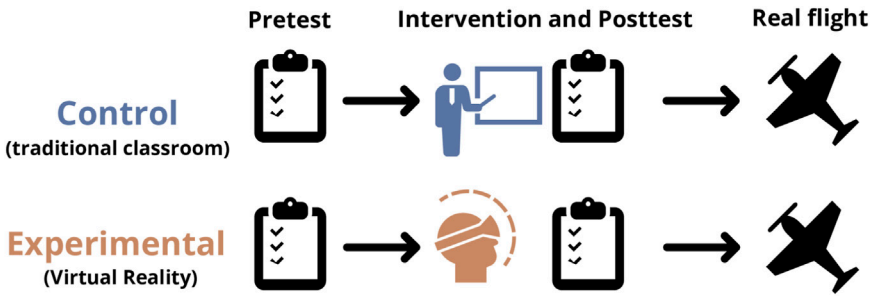


FIGURE 2
Control and Experimental group treatment. All participants completed a knowledge pretest prior to the intervention. Participants in the control group attended a 45-min instructor-led classroom session covering the DA20 aircraft's instrumentation and flight procedures. The experimental group, however, completed a 45-min VR session simulating their upcoming flight with a flight instructor. Immediately after the intervention, all participants completed a posttest, followed by a real flight several days later.

that both the control and experimental training interventions occurred as close as possible to the participants' first flights, ideally within 1 week prior. However, due to factors such as instructor, aircraft, and airport availability, as well as meteorological conditions, the time between the training session and the first flight varied, a correlation analysis between days elapsed and real flight marks were performed to assess whether the time elapsed could represent a potential confounding factor.

2.3 Instruments

A questionnaire was developed to assess participants' understanding of key concepts necessary for a pilot's first real flight, all of which were covered in the DA20 course. The questionnaire included five questions in various formats, such as identifying instruments from cockpit images, sequencing a specific flight procedure, and completing a table with aircraft configuration data.

The same questionnaire was delivered twice: as a pretest and then as a posttest (Tesch, 2016). The pretest was conducted in person for all participants on the same date, days after the completion of the DA20 course. The posttest was provided individually to participants after they completed their respective control or experimental training sessions, on different dates.

Each pilot's performance during their first real flight was assessed using a standardized rubric approved by Agencia Estatal de Seguridad Aérea (AESA) under regulation (UE) n° 1178/2011. The flight instructor evaluated 23 different aspects of the flight using a three-level rubric-based scale. These individual ratings were then automatically compiled into a single overall performance score. This data was collected for both the control and experimental groups to measure and compare their actual flight performance.

The effective instruments for qualitative analysis of the sessions were the instructors' notebook, student interviews, and a focus group with representative students. During the VR experiments, the sessions were recorded to have a detailed account of everything that happened: the behaviour of both students and instructors, with a broad view of the room (Williams et al., 2014). Additionally, the computer screen showing what the students saw through the VR headset and documents with annotations were also recorded (Williams et al., 2014). However, these recordings were only used for occasional consultation in case other instruments required clarification on any specific detail.

The instructors' *notebook* consisted of a set of questions that the instructors were asked to answer at the end of each session. Instructors were requested to register written evidence of the relevant topics using the technique of direct observation through a record of notes that condense answering some key questions (Creswell, 2013). To reach responses aiming at a relevant synthesis to evaluate each experience, the posed questions were: Q1: Does the student follow the class well? Q2: How does the student perform the manoeuvres? How do they read the instruments? Q3: What is the student's reaction to VR? Difficulties or admiration? Q4: Did the student experience any motion sickness? Q5: Were there any technical difficulties? Q6: Note any extraordinary events.

In parallel, each student participating in the VR experiment was also required to respond to a structured *interview* (Williams et al., 2014; Creswell, 2018) about their impressions of the experience. This information complements the students' perspectives and evaluations of the proposal. The questions posed were: Q1: How do you think using VR influenced your flight training preparation? Q2: What do you think are the advantages of VR in this type of training? Q3: What do you think are the disadvantages of VR in this type of training? Q4: How do you think this training could be improved using VR? Q6: Do you think VR can replace some real flights?

Finally, to reach data saturation, a *focus group* was conducted with two participants interviewed together to delve deeper into the understanding of the results obtained with the other instruments.

Considering that the volume of the data collected was not extensive, the analysis process involved a thorough reading and organization of the information. Patterns were identified, and connections between ideas were explored using both a text editor and a spreadsheet. The text editor allowed for structuring and annotating key findings, while the spreadsheet was used to categorize and cross-reference data points systematically. This method facilitated the identification of recurring themes and relationships within the dataset, ensuring a comprehensive understanding of the qualitative information collected.

All questionnaires were distributed via Microsoft Forms. Boxplots were generated via python 3.11.

3 Results

3.1 Applied skills

The boxplot in Figure 3 shows the distribution of marks for the real flight performed by students, categorized into control and experimental groups. Note that the experimental group, which used VR training, achieved higher marks than the control group. Instructors were not aware of the student's group at the time of evaluation. Two students were excluded from this section of the results, one from each of the control and experimental groups, because they were late to the real flight session. In such cases, the instructor assigns a score of 5 regardless of performance.

Although the Shapiro-Wilk test did not reject normality (experimental group: $p = 0.65$, control group: $p = 0.26$), the Levene's test indicated heteroscedasticity ($p = 0.0077$), and together with the small sample size, we adopted a non-parametric approach. Consequently, the Mann-Whitney U test was applied to compare the medians between the experimental and control groups. The test yielded a U statistic of 39 with a p-value of 0.019, confirming a significant difference between the groups. The effect size, calculated using the rank biserial correlation was 0.494, indicating a moderate effect.

The number of days between the intervention and the real flight varied due to meteorological constraints and the practical limitations of conducting the study in an authentic academic

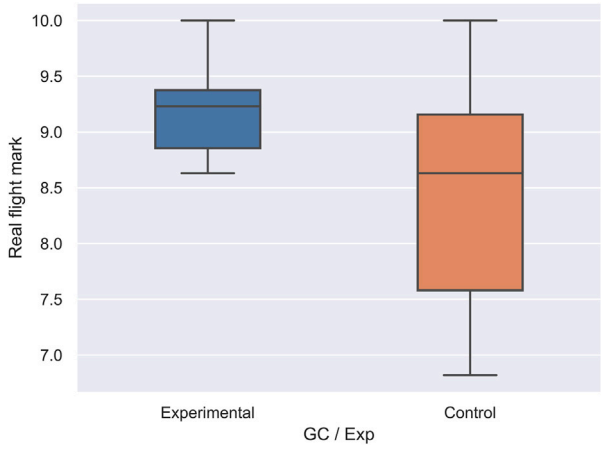


FIGURE 3
Boxplot of the marks for real flights performed by students in control and experimental groups. The experimental group, which used VR training, achieved higher marks than the control group. A Mann-Whitney test resulted in a p-value of 0.0194.

setting. Thus, days elapsed represent an extraneous variable with potential confounding effects on the results. Therefore, we computed the Spearman correlation between days elapsed and real flight marks separately for the control and experimental groups, using a non-parametric approach given the non-normality of days elapsed (experimental group: $p = 0.0022$, control group: $p = 0.0004$). The results showed no statistical correlation between days elapsed and real flight marks either in the control group ($\rho = -0.0297$, $p = 0.931$) or in the experimental group ($\rho = 0.019$, $p = 0.948$).

3.2 Theoretical knowledge

The pretest and posttest questionnaires, conducted before and after the intervention, will shed light on the theoretical knowledge gained from each method: VR in the experimental group and traditional classroom in the control group.

In Figure 4, the pretest scores were similar for both groups. While both groups exhibited an increase in posttest means compared to their pretest scores (control group increase a 25.9% and experimental group increase a 15.3%), a paired t-test indicated that the increase in the control group was statistically significant ($p = 0.001$), whereas the increase in the experimental group was not significant ($p = 0.145$).

3.3 Instructors' notebook

Instructors consistently observed that students adapted quickly to the VR environment. Nearly all students required only a short familiarization period before effectively executing the flight manoeuvres, which suggests that the VR is intuitive and accessible for most students. For instance, Instructor3, speaking about participant10, noted that *"after a few minutes of exploration, the student was able to execute manoeuvres smoothly."* This suggests that VR offers an accessible platform for training, even for those unfamiliar with the technology.

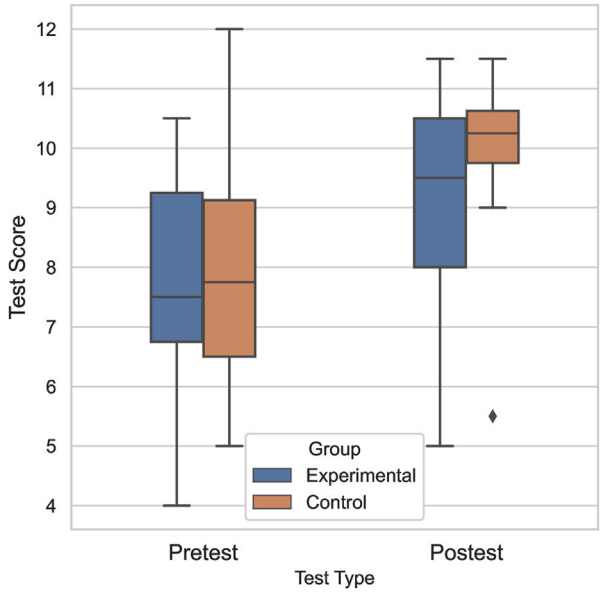


FIGURE 4
Boxplot of the pretest and posttest scores by students in control and experimental groups. Pretest scores were similar for both groups. Although both groups exhibited higher posttest means, a paired t-test indicated that the increase in the experimental group, which used VR training, was not significant ($p = 0.145$), whereas the increase in the control group, under a traditional classroom, was statistically significant ($p = 0.001$).

Students showed positive attitude and perceptions. Overall, instructors informed that the students leave happy from the mission, feeling as if you were inside the plane, that students conveyed having enjoyed the experience, satisfaction, in seven cases "admiration" is communicated (a word that was mentioned in the question posed, which certainly have influenced in the responses), also two instructors highlight the realism, and one instructor remembered how an student emphasized that this experiment can be done from anywhere putting in value the geographical advantage.

The overall performance of the students in the VR training showed a pattern of initial difficulty followed by significant improvement as they became more familiar with the controls. Most students struggled with maintaining altitude and speed at the beginning, as they adapted to the flight instruments and procedures. However, there was a notable improvement during the sessions, and by the end of the experiment, many were able to control essential flight parameters effectively. As Instructor1 noted about participant11: "*The student took a little time to get to grips with the controls of the plane, which made it difficult for him to maintain altitudes and speeds at the beginning, but a considerable improvement was observed during the flight, which allowed him to finish the mission being able to control the parameters.*" Other participants aligned with this evolution.

Asked about how students do the manoeuvres and how do they read the instruments, the instructors are mostly satisfied with the students' performance, yet there is room for improvement in some cases: "*Attitude must be improved during the flight*" (Instructor2 about Participant15), "*sometimes he does not remember well the order to level up or down*" (Instructor3 about Participant18), "*he had to be reminded during the manoeuvre a certain step to follow (especially the TRIM aspect)*" (Instructor3 about Participant16), "*the student makes several errors both in reading and executing the manoeuvre, and on several occasions is not able to maintain the parameters*" (Instructor1 about Participant21), and "*it is a little difficult for him to do the scan flow*" (Instructor2 about Participant28). Such improvement needs are likely to be related to the fact that this is their first flight rather than the VR aspect. Instructors do not deny that the errors in VR could affect a better performance in the first real volume.

When it comes to more complex flight scenarios faced by students, Instructors reported varied performance. Several instructors observed that students struggled with the absence of physical feedback during critical moments. For instance, difficulty managing an engine failure scenario, attributing the challenge to the lack of sensory input, such as the feeling of turbulence or changes in aircraft motion. This was a common issue among students handling high-stress tasks, which aligns with the students' feedback regarding the limitations of VR.

The instructors observed occasional ergonomic and technical challenges that hindered student performance. For instance,

Instructor4 observed that participant9 struggled with the pedal layout, which interrupted the flow of their session. In another case a little physical discomfort after having dressed the glasses for a long time was reported. These situations were exceptional and in future experiments could be easily addressed, not implying a potential limitation of this technology. On the other hand, problems with controls such as the ignition switch were reported in given cases. Instructor 2 comments that "*the biggest problem was the remote, having to press the buttons with the mouse on the part of the instructor and the position of the flaps under the gas*." Although these issues were not widespread, they did occur across multiple students, indicating that certain elements of the VR setup could be improved for better alignment with real cockpit ergonomics and technical quality.

Looking at potential technical difficulties related to the software; in four cases the instructors confirm none. The rest reported varied technical issues during the VR training. The most remarkable is that the engine key was hard to use. It refers to the key to start the engine (we refer to the aircraft key, as we switch the key in a car to run the engine). VR works very well if you have the analogical buttons, as with the remotes you must force an imaginary movement and feels more unnatural. Additionally, it was occasionally reported that the ignition switch was difficult to turn and using the mouse to operate buttons like the fuel pump increased reaction time during flight. It should be noted that such mouse interaction is performed by the instructor, not by the students, used only for secondary cockpit functions for which no physical hardware was available. All primary flight controls used by the students (stick, rudder pedals, throttle and flaps) were operated through real physical devices.

Instructors are asked about any cases of dizziness, and they confirmed that there have been none. Only in one case is it reported that "*At first it was difficult for him to see due to the use of glasses, which caused him a little dizziness, but then everything came fine*" (Instructor1 about Participant19).

Also, should be considered that the starting warning light and the TRIM could be improved. In some case it was said that the push-to-test lights and warning lights were either malfunctioning or poorly simulated. This is acknowledged because of the specific software, and the model of the plane offered. Other isolate technical issues refer to issues with the aircraft's power, which initially prevented take-off until the session was restarted. An instructor also remarks that a student noted difficulty in reading the instrument numbers clearly.

Instructors held a generally positive view of VR as a training tool, though they emphasized the importance of integrating it with real-world flight practice. Most instructors noted that the realism of the simulations helped students feel more prepared for actual flights, but they also recognized the limitations. Instructor2, reflecting on participant7's session, commented that "*the student appreciated how closely the VR cockpit matched the real one, but acknowledged that it does not fully replace the feel of actual flight*." This perspective reinforces the notion that VR serves as a valuable training tool, but always in a supplementary manner.

Another relevant aspect to consider is that these experiments were designed to boost the practical part of the training. In this regard, previsible results related to the lack of memorisation and theoretical reinforcement were reached. Several impressions aligned to this situation, like Instructor1 reported stating that "[the student] *shows difficulty understanding and applying the concepts, if the instructor is not constantly reminding them*", and Instructor 2 pointing out that "[the student] *lacks more background*", among other comments in this line.

In overall the impression is highly positive both from the instructors' side and from what the instructors have seen from students' reactions: "*There was surprise by the reality of the simulation, it is a perfect tool to improve the skills of students with more difficulties to face a specific mission*" because "allows you to get a familiarization before the flight" (Instructor2). Despite the challenges, both students and instructors reacted positively to the overall VR training experience. Many students left the sessions feeling more confident in their ability to perform in real-world scenarios. Instructor2, who observed participant7, noted that *"the student expressed satisfaction with how closely the VR simulation resembled actual flight, especially in terms of cockpit layout and procedure repetition."* This enthusiasm was shared by many participants, instructors said.

3.4 Students' interviews

Students perceived VR as an effective and valuable tool for flight training, it has a positive impact on their flight preparation. 12 students (86%) believed that VR significantly enhanced their ability to perform flight manoeuvres, and several emphasized how VR enhanced their spatial awareness and allowed them to practice procedures in a controlled, immersive environment. On the other hand, 8 students (57%) acknowledged the limitations of VR in replicating physical sensations or minor technical difficulties. Despite some technical issues and physical discomfort, the consensus was that VR serves as a critical bridge between theoretical knowledge and real-world flight experience, with the potential to greatly enhance training outcomes when used in conjunction with traditional flight practice.

3.4.1 Perceived advantages of VR in flight training

Several advantages were frequently mentioned by students, most notably the realism of the VR environment. Thus, a key theme emerged from the interviews was the positive impact of VR on students' immersion and spatial awareness. Out of 14 students, 10 (71%) highlighted that the virtual environment helped them develop a better understanding of the cockpit layout and the spatial dynamics of flight. For instance, participant11 mentioned that "*the VR training made it easier to visualize my position in the cockpit during manoeuvres*", and Participant11 remarked that VR provided a strong sense of being in a real scenario, which helped with understanding spatial orientation during complex movements. Most students echoed this sentiment, indicating that the immersive nature of VR contributed to their preparedness for real-world flight scenarios.

The ability to repetitively practice specific flight procedures in a risk-free environment was another frequently mentioned benefit. 12 out of 14 students (86%) expressed that VR allowed them to focus on and perfect challenging manoeuvres. Participant13 stated that "*I was able to repeat the landing procedure multiple times until I felt confident*" in "*a way to practice without distractions*", a comment that reflects the overall value placed on repetition, the ability to

repeat challenging movements in a safe, focused setting. Similarly, participant8 emphasized how VR enabled them to isolate and practice difficult sections of a flight, such as emergency scenarios, with an attention to detail that is harder to achieve in real-life training. Thus, this feature was seen as particularly useful for mastering emergency scenarios and developing procedural memory.

Another highlighted theme was the safety of VR, allowing students to build confidence by practicing risky procedures in a virtual environment. Many students valued the ability to rehearse manoeuvres without the potential consequences of real-world errors. This finding was consistent across most participants, reinforcing the perception that VR provides a crucial bridge between theoretical knowledge and practical skill.

Students appreciated the potential of VR as a complementary tool to traditional flight training. However, they emphasized that it cannot replace actual flight experience. Both students and instructors consistently highlighted the importance of integrating VR with real-world practice to ensure well-rounded training. The combination of virtual and real flight practice was viewed as essential for developing both the cognitive and physical skills necessary for piloting an aircraft.

3.4.2 Disadvantages and limitations of VR

Despite the widespread appreciation for VR, some disadvantages were reported across participants. One of the most noted limitations was the absence of physical sensations, which is considered a critical lack regarding the importance of the G-forces or vibrations during actual flight. Eight students (57%) mentioned that VR lacked important physical feedback, which they felt was necessary for a fully realistic training experience. Participant7 noted, "*It is hard to react naturally to flight situations without feeling the motion of the plane*", adding that "*While it feels real in many ways, I miss the physical sensation of movement, which is important when flying in the real world*", and Participant15 noted that *"without the feeling of movement, it is hard to gauge certain aspects like the response to turbulence."* This issue was reiterated by other participants, suggesting that while VR is highly immersive visually, it falls short in replicating the full sensory experience of flight.

Another recurring issue was related to the resolution and clarity of the VR headsets. Participants found that certain instruments were difficult to read, especially during key phases of flight such as take-off and landing. Participant12 explained how *"some of the instruments were blurry, making it harder to focus during critical moments."* This technical limitation was also noticed by the instructors, although students generally acknowledged that this did not outweigh the broader benefits of VR.

While most students adapted well to VR training, 3 participants (21%) reported mild symptoms of motion sickness or discomfort during longer sessions. Participant5 noted feeling slightly dizzy after extended use, though they still appreciated the overall training experience. The discomfort experienced by a minority of students suggests that session duration may need to be optimized to maintain effectiveness without causing physical strain. This result only aligns partially with the instructors' annotations, as they reported just one case of initial dizziness.

Both students and instructors reported technical issues, although these were not severe enough to undermine the overall effectiveness of the training. Problems with certain controls and cockpit ergonomics were noted by multiple participants and instructors. For example, (as already reported from the instructors' notebooks), the ignition switch, lighting realism and pedal adjustments were problematic. Students talk about these issues but not as major problems.

3.5 Focus group

The two instructors inform having observed significant improvement in students' understanding of concepts related to aircraft, particularly in terms of instrument positioning and procedures. This allowed them to be better prepared for their first flights, reducing the need for repetition during briefing and flight.

As the interviewees convey, VR enables students to experience visual flights with nearly 360° vision, improving their spatial awareness and ability to carry out procedures correctly, such as flap control. This is a remarkable improvement compared to traditional simulators, which focus more on instrumental flights.

VR offers the ability to correct common mistakes in a safe environment, allowing students to improve their skills before flying in real conditions. This aspect was seen in previous data collection, and the focus group reinforced its meaningfulness. Additionally, unlike traditional simulators, VR allows for much faster mission setup and start times, reducing waiting time and increasing efficiency during training sessions.

As emerged from the focus group, instructors confirm good adaptability to the technology and a positive attitude, ending sessions with enthusiasm as already introduced in the notebooks. VR not only helps students learn but also motivates them to keep improving thanks to a highly enriching practical experience. As one interviewee stated: "*The first thing you see in them when they take off the headset is a smile*".

4 Discussion

Simulation is an experiential instructional approach that recreates real-world situations, allowing learners to apply knowledge and skills in contextualized, practice-based environments (Jones and Barrett, 2017). By fostering active, integrated, and situated learning processes, it represents a powerful strategy for enhancing meaningful learning and skill development (Jones and Barrett, 2017). VR has been proven to be effective in training skills in studies across diverse disciplines: Kennedy et al. (2023) found that the VR practical experience reduced errors among medical students compared to traditional training; Chen et al. (2020) demonstrated that integrating VR into STEAM teaching improved senior high school students' learning outcomes and practical skills. Conversely, Lui and Goel (2022) found no significant difference between real-world hospitality training and VR hospitality training. The fields in which VR training can effectively support real-world situations still need further study.

In aviation studies, as stated by researchers such as Hight et al. (2022), VR simulations can be an effective instructional tool in civilian *ab initio* pilot training, providing immersive and practice-oriented experiences that support the development of relevant skills in future pilots. However, a review by Ross and Gilbey (2023) highlights the limited research on VR in this field. Most existing studies have been presented at conferences and published as proceedings rather than journal articles. Additionally, most studies focus on military training, and research from flight schools appears to be limited. As examples, Pennington et al. (2019) introduced VR in initial flight training, observing an increase in self-efficacy in military pilots. Dymora et al. (2021) demonstrated the effectiveness of VR technology in commercial pilot training, although their findings were based on an eight-question survey. Ross and Gilbey (2023) also conclude that VR could support traditional flight training, which aligns well with our findings, highlighting the need for more rigorous research with civil aviation as a priority.

In our study, we observed that the scores achieved by participants during their first real flight in the experimental group statistically outperformed those of the control group, with a moderate effect size. This finding indicates that VR training has enhanced the skills of student pilots more effectively than traditional classroom teaching, confirming our expectations in Hypothesis 1. Our findings can also be interpreted within the CAMIL framework (Makransky and Petersen, 2021), in which student pilots may benefit from the immersive VR experience through an increased sense of presence and agency. The use of the same airport, aircraft, and reduced visual aids provided high representational fidelity. In addition, student's sense of agency may have been strengthened by interacting with physical flight instruments during the VR experience. Taken together, these design features may have increased students' confidence during the first real flight, as reported in both instructor and student interviews. Within the CAMIL framework, this increased confidence may be associated with enhanced self-efficacy.

Our findings should be interpreted considering that student enthusiasm and perceived confidence may be partially influenced by the novelty effect associated with immersive VR environments, whereby initial fascination with new technology may affect learning experiences and outcomes (Miguel-Alonso et al., 2024).

On the other hand, both VR and traditional classroom training led to an increase in flight knowledge. This increase was greater in the traditional classroom, with a 25.9% mean improvement compared to 15.3% after the VR flight session, and only the traditional classroom showed a statistically significant improvement. Several studies highlight that the acquisition of knowledge through VR is not significatively different than through traditional classroom teaching (Jensen and Konradsen, 2018; Sichterman et al., 2023; Šikl et al., 2024). Some studies find VR more effective than traditional teaching, while others find it less effective, depending on the field of application (Mayer et al., 2023; Ma et al., 2019; Rasheed et al., 2015). One possible explanation for this result is that our learning activity was primarily designed to improve flight skills, whereas the pretest and posttest questionnaires focused more on theoretical knowledge, because they were based on the theoretical exam students must pass before beginning flight training.

The finding that the control group achieved a statistically significant improvement in theoretical knowledge may be understood through CAMIL (Makransky and Petersen, 2021), together with Cognitive Load Theory (Sweller et al., 2011). According to CAMIL, immersive VR environments enhance learning through the affordances of presence and agency, which intensify attention, engagement, and action-based processing. However, these same affordances can also amplify extraneous cognitive load when the environment provides high sensory fidelity without sufficient instructional guidance. In this sense, recent multi-day training research with immersive VR has shown that, although such technology can complement skill acquisition, it is associated with higher cognitive load and, in some cases, lower learning outcomes compared to control conditions (De Witte et al., 2026). In our case, the rich perceptual input and interaction demand of the VR flight simulation likely required learners to allocate substantial cognitive resources to navigation and sensorimotor coordination, limiting the resources available for the construction of theoretical. It was intended to be as realistic as possible, with no distracting elements, but the inherent characteristics of the technology may have had some impact. From this perspective, the lower gains in theoretical knowledge schemas can be understood as a transposition challenge between procedural experience and conceptual understanding. The immersive system provides action-oriented feedback but lacks explicit regulatory mechanisms that guide learners in abstracting principles from theory and experience.

We propose to study whether a pre-training session similar to the one given to the control group could be included before the VR training flight in future studies. This could help reduce cognitive load during the VR session and support better results in knowledge, transfer, and flight performance (Meyer et al., 2019). Another possibility would be to incorporate adaptive scaffolding within the VR simulation to reduce extraneous cognitive load and better support the integration of procedural and theoretical learning. For example, support could include highlighting relevant instruments during the initial instrument-recognition phase, as well as brief feedback delivered immediately after take-off, manoeuvres, and landing to help learners connect the procedures they have just performed with their underlying theoretical principles.

Even if "it is still unclear what the effectiveness of VR is in short- and long-term training of pilots" (van Weelden et al., 2021), we support in positive that the students in this study adapted quickly to the VR environment, they showed a positive attitude and perceptions, and they had to adapt to the new technology, but it was a quick process and became more familiar with the controls, as in other contexts (Arbués Garcia del Moral et al., 2024). Studying the performance in a qualitative manner, they managed the manoeuvres successfully, but some aspects must be considered and remarked absence of physical feedback during critical moments as a lack from this experience. Other difficulties that have been identified and match with other studies are occasional ergonomic and technical challenges, technical difficulties related to the software, and the fact that the starting warning light and the TRIM could be improved. Even though, these have not been labelled as crucial and with better resources could be solved.

Aspects such as emergency procedures and spatial awareness are highlighted in the literature as factors that enhance training

effectiveness in the development of piloting skills (Somerville et al., 2025). We observed that a strong point for students was the immersion and spatial awareness, aligned with Cross J. I. et al. (2023), as well as the VR provision of a strong sense of being in a real scenario. Other positive aspects reinforced the benefits reported in other experiences as it appears that participants highlight the importance of integrating it with real-world flight practice and participants in the experimental part left the session feeling more confident in their ability to perform in real-world scenarios (Chen et al., 2020).

Several studies have highlighted challenges of VR in educational settings. For instance, research has shown that cybersickness remains a significant barrier (Rebelo et al., 2012; Jensen and Konradsen, 2018; Ross and Gilbey, 2023), although in the case of aviation, it is reduced when seated (Kim et al., 2023). Probably due to the limited number of participants, we found that none of them expressed dizziness, only one participant reported an initial sense of it, but the flight session was ultimately carried out normally. The literature refers cybersickness in the use of VR for educational purposes (Jensen and Konradsen, 2018), but our finding aligns with the fact that pilots managing the VR aircraft tend to experience less cybersickness than VR passengers or instructors in passive roles (Rebelo et al., 2012). This topic has been dealt in previous studies (Patrão et al., 2020) with no concluding results but tending to agree little prevalence. At the end, it can be effective as an adaptive tool for pilot training (Aguilar Reyes et al., 2023).

Finally, the introduction of a novel technology can be challenging for teachers (Bower et al., 2020). In this study, the flight sessions were carried out under the supervision of an investigator who resolved all technical issues. We suggest creating a tutorial for instructors if VR is to be used by a novice instructor alone.

5 Conclusion

This study aimed to evaluate the effectiveness of virtual reality (VR) in enhancing pilot learning skills and to explore the perspectives of both students and instructors regarding its use. Even considering the potential novelty effect associated with the use of VR (Miguel-Alonso et al., 2024), our findings provide strong evidence that VR training significantly improves student pilots' practical flight skills, confirming Hypothesis 1. The experimental group, which trained with VR, demonstrated superior performance during their first real flight compared to the control group, despite VR training showing a smaller improvement in theoretical knowledge than traditional classroom instruction. This aligns with prior research that suggests VR is particularly beneficial for skill acquisition but may be less effective for purely theoretical learning. VR can result in breaks in presence (Ross and Gilbey, 2023), but the high latency provided by the high-quality computer probably reduced this issue. Other studies suggest that VR can distract form the learning task, hindering the acquisition of concepts (Mayer et al., 2023), but in our case VR must reliably simulate reality, then a simulated flight with VR can not be more distracting than a real flight. As discussed, this intriguing difference (the control group performing better in theoretical learning) can be explained by the Cognitive Load Theory.

Additionally, participants recognized the potential and practicality of VR in pilot training, supporting Hypothesis 2. They reported a high level of engagement, improved spatial awareness, and increased confidence in real-world scenarios after VR training. The literature identifies spatial awareness as a contributing factor in the development of piloting skills (Somerville et al., 2025). Although some limitations, such as the lack of physical feedback and occasional technical difficulties, were identified, these challenges were not deemed critical and could be mitigated with improved resources and design. Importantly, cybersickness, a common concern in VR applications, was not significantly reported among our participants, possibly due to the nature of flight training and the immersive qualities of the VR system used.

While VR cannot replace actual flight experience, it serves as a valuable supplementary tool for pilot training, offering a safe and adaptable environment for repeated practice, including emergency procedures and airport approach training. Future research should focus on optimizing VR-based learning experiences for aviation concepts and addressing the integration of VR with traditional flight instruction. The findings of this study have several important implications for pilot training programs and aviation education. The demonstrated effectiveness of VR in improving flight skills suggests that integrating VR into existing pilot training program could provide students with additional practice opportunities in a safe and controlled environment. This could be particularly useful for mastering manoeuvres, emergency procedures, and airport approach scenarios before actual flight sessions. Additionally, the positive reception from students and instructors highlights VR's potential as a motivational and engaging tool for flight training. Based on the advantages defined by Rebelo et al. (2012), the adaptability and safety of VR enable flight instructors to design lessons allowing student pilots to practice approach procedures at different airports worldwide. This provides a controlled and safe environment for repeated practice, such as emergency procedures, an interesting future line of investigation.

From a broader perspective, the study supports the growing body of evidence that VR can be an effective training tool across various fields requiring practical skill development. VR is particularly effective in the initial stages of pilot training, supporting procedural familiarization, spatial orientation, and basic decision-making. However, for advanced training phases requiring high-fidelity instrument interaction and complex avionics, FSTDs remain the more appropriate training solution. The aviation industry, regulatory bodies, and training institutions should consider expanding their investment in VR-based training solutions, particularly for early-stage pilot education. However, while VR enhances skill acquisition, its limitations in theoretical knowledge retention suggest that it should complement, rather than replace, traditional classroom instruction.

Our results highlight a challenge in supporting theoretical knowledge acquisition through VR, as the control group outperformed the VR group in conceptual post-tests. From the perspective of the Cognitive Affective Model of Immersive Learning (CAMIL; Makransky and Petersen, 2021), the high sensory fidelity and immersive interaction of the VR system increased presence and agency, which effectively supported procedural learning. However,

these same affordances can generate extraneous cognitive load when learners lack sufficient scaffolding, reducing cognitive resources available for theoretical schema construction (Sweller et al., 2011).

To address this, future VR designs could include a pre-training session or briefing mirroring the control group's instruction, to activate relevant schemas and reduce cognitive load during VR tasks (Meyer et al., 2019). From a human-computer interaction and a technical perspective, VR simulations can be enhanced to support self-regulated learning and mitigate extraneous load. Computational affordances such as adaptive scaffolding, integrated within the virtual cockpit could dynamically guide learners toward key theoretical principles while maintaining immersive realism (Hsu and Lee, 2026). Further research should examine these approaches while carefully considering their potential impact on representative fidelity.

Despite the promising results and possibilities, this study has several limitations. The sample size was relatively small, which may limit the generalizability of the findings, as recruiting pilot students is inherently challenging; however, all participants were student pilots engaged in a real-world training context, adding value as it reflects authentic training conditions rather than simulated or hypothetical scenarios. The time interval between the VR intervention and the participants' first real flight varied from 1 day to 1 month due to operational constraints, though analyses showed no meaningful association with performance. Although the odd/even blocked allocation based on ranked final marks helped maintain initial balance between groups, it remains a quasi-experimental method rather than a fully randomized controlled trial, leaving a small possibility that some unmeasured characteristics could have been unevenly distributed. The study focused primarily on short-term skill acquisition and immediate performance, leaving long-term retention of VR-trained skills and knowledge as an open question. Finally, minor technical issues, such as occasional software glitches and ergonomic discomfort, were noted, highlighting the need for continuous improvement in VR hardware and software to enhance reliability and user experience.

From this research different lines can be pointed:

1. Assess whether the benefits observed in VR training persist over time and translate into sustained performance in real-world flight scenarios.
2. Studies should investigate whether the skills gained through VR training are retained over extended periods and how they translate into actual flight performance over time.
3. Research with larger and more diverse groups of participants, including pilots at different training stages and from different training institutions, would provide more generalizable insights.

Data availability statement

Datasets are available on request: the raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The Research involving Human Participants and/or Animals, in accordance with the guidelines approved by the ethical committee under code CEIPSA-2023-PR-0029 (Universitat Rovira i Virgili). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

TV-C: Writing – review and editing, Software, Conceptualization, Visualization, Funding acquisition, Resources, Investigation, Project administration, Formal Analysis, Validation, Writing – original draft, Methodology, Data curation, Supervision. JM-R: Funding acquisition, Investigation, Conceptualization, Data curation, Formal Analysis, Writing – review and editing, Writing – original draft, Methodology, Software, Supervision. CN-M: Investigation, Conceptualization, Resources, Writing – original draft. RP: Funding acquisition, Supervision, Conceptualization, Data curation, Visualization, Validation, Methodology, Writing – review and editing, Writing – original draft, Software, Investigation.

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References

Aguilar Reyes, C. I., Wozniak, D., Ham, A., and Zahabi, M. (2023). Design and evaluation of an adaptive virtual reality training system. *Virtual Real* 27, 2509–2528. doi:10.1007/S10055-023-00827-7/METRICS

Airbus (2022). Global services forecast (GSF) | 2024-2043. Available online at: https://aircraft.airbus.com/en/global-services-forecast-gsf-2024-2043 (Accessed December, 31, 2025).

Alves Fernandes, L. M., Cruz Matos, G., Azevedo, D., Rodrigues Nunes, R., Paredes, H., Morgado, L., et al. (2016). Exploring educational immersive videogames: an empirical study with a 3D multimodal interaction prototype. *Behav. Inf. Tech.* 35, 907–918. doi:10.1080/0144929X.2016.1232754

Arbués Garcia del Moral, J., Codesal Patiño, M. B., Cuadrado Sáez, M. L., Ferré-Huguet, N., García Taravilla, V.M., Garcia Vega, A., et al. (2024). "La realitat augmentada, la realitat virtual i el metavers en la societat," in *Impacte a l'educació*. Barcelona, Spain: Universitat de Barcelona (Institut de Desenvolupament Professional). Available online at: http://hdl.handle.net/2445/215523.

Boeing (2022). *Pilot and technician outlook 2022-2041*.

Bower, M., DeWitt, D., and Lai, J. W. M. (2020). Reasons associated with preservice teachers' intention to use immersive virtual reality in education. *Br. J. Educ. Tech.* 51, 2215–2233. doi:10.1111/BJET.13009

CAPA - Centre for Aviation (2023). Women airline pilots: numbers are growing, but still a pitiful percentage. Available online at: https://centreforaviation.com/analysis/reports/women-airline-pilots-numbers-are-growing-but-still-a-pitiful-percentage-655755 (Accessed December 31, 2025).

Caro, P. W. (1973). Aircraft simulators and pilot training. *Hum. Factors* 15, 6 502–509. doi:10.1177/001872087301500602

Chen, J. C., Huang, Y., Lin, K. Y., Chang, Y., Lin, H., Lin, C., et al. (2020). Developing a hands-on activity using virtual reality to help students learn by doing. *J. Comput. Assist. Learn.* 36, 46–60. doi:10.1111/JCAL.12389

Creswell, J. W. (2013). *Qualitative inquiry and research design: choosing among five approaches*. 3rd edn. Washington DC: SAGE Publications.

Creswell, J. W. (2018). *Research design: qualitative, quantitative, and mixed methods approaches*. 5th edn. Washington DC: SAGE Publications.

Cross, J., Boag-Hodgson, C., Ryley, T., Mavin, T. J., and Potter, L. E. (2023). "Using extended reality in flight simulators: a literature review," in *IEEE transactions on visualization and computer graphics* (IEEE Trans Vis Comput Graph), 3961–3975. doi:10.1109/TVCG.2022.3173921

Cross, J. I., Boag-Hodgson, C. C., and Mavin, T. J. (2023). Measuring presence and situational awareness in a virtual reality flight simulator. *Aviat. Psycho. Appl. Hum. Fact.* 13, 83–94. doi:10.1027/2192-0923/a000250

De Witte, B., Reynaert, V., Kieken, D., Jabbour, J., Demarey, C., Dumoulin, A., et al. (2026). Immersive virtual reality learning and cognitive load: a multiple-day field study. *Comput. Hum. Behav.* 176, 108853. doi:10.1016/j.chb.2025.108853

Ding, X., and Li, Z. (2022). A review of the application of virtual reality technology in higher education based on web of science literature data as an example. *Front. Educ. (Lausanne)* 7, 1048816. doi:10.3389/FEDUC.2022.1048816/BIBTEX

Dymora, P., Kowal, B., Mazurek, M., and Śliwa, R. (2021). "The effects of virtual reality technology application in the aircraft pilot training process, " in *IOP Conference Series: Materials Science and Engineering, 10th EASN International Conference on Innovation in Aviation & Space to the Satisfaction of the European Citizens* (10th EASN 2020), 2nd-5th September 2020. 1024.

Egan, D., Brennan, S., Barrett, J., Qiao, Y., Timmerer, C., and Murray, N. (2016). "An evaluation of heart rate and ElectroDermal activity as an objective QoE evaluation method for immersive virtual reality environments," in 2016 8th international conference on quality of multimedia experience, QoMEX 2016. doi:10.1109/QOMEX.2016.7498964

Estupiñán, S., Rebelo, F., Noriega, P., Ferreira, C., and Duarte, E. (2014). "Can virtual reality increase emotional responses (Arousal and Valence)? a pilot study," in *Design, user experience, and usability. user experience design for diverse interaction platforms and environments*. Editors A. Marcus (Cham: Springer), 184–213. doi:10.1007/978-3-319-07626-3_51

Guthridge, R., and Clinton-Lisell, V. (2023). Evaluating the efficacy of virtual reality (VR) training devices for pilot training. *J. Aviat. Tech. Eng.* 12, 1. doi:10.7771/2159-6670.1286

Hight, M. P. H., Fussell, S. G., Kurkchubasche, M. A., and Hummell, I. J. (2022). Effectiveness of virtual reality simulations for civilian, *ab initio* pilot training. *J. Aerosp. Educ. Res.* 31:1. doi:10.15394/jaaer.2022.1903

Hsu, Y. T., and Lee, S. W. Y. (2026). Support for self-regulated learning in immersive virtual reality – an experimental design for science learning. *Educ. Inf. Technol.* 31, 269–300. doi:10.1007/s10639-025-13807-y

Jensen, L., and Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. *Educ. Inf. Technol. (Dordr)* 23, 1515–1529. doi:10.1007/S10639-017-9676-0/METRICS

Jones, J. D., and Barrett, C. (2017). Simulation as a classroom teaching method. *i-Manag. J. Sch. Educ. Technol.* 12, 4 49–53. doi:10.26634/jsch.12.4.13551

Kakkos, I., Dimitrakopoulos, G. N., Gao, L., Zhang, Y., Qi, P., Matsopoulos, G. K., et al. (2019). Mental workload drives different reorganizations of functional cortical connectivity between 2D and 3D simulated flight experiments. In IEEE Transactions on Neural Systems and Rehabilitation Engineering. 27, (9) 1704–1713. doi:10.1109/TNSRE.2019.2930082

Kavanagh, S., Luxton-Reilly, A., Wuensche, B., and Plimmer, B. (2017). A systematic review of virtual reality in education. *Themes Sci. Tech. Educ.* 10, 85–119. Available online at: https://files.eric.ed.gov/fulltext/EJ1165633.pdf.

Kennedy, G. A. L., Pedram, S., and Sanzone, S. (2023). Improving safety outcomes through medical error reduction *via* virtual reality-based clinical skills training. *Saf. Sci.* 165, 106200. doi:10.1016/J.SSCI.2023.106200

Kim, A., Lee, J. E., and Lee, K. M. (2023). Exploring the relative effects of body position and locomotion method on presence and cybersickness when navigating a virtual environment. *ACM Trans. Appl. Percept.* 21, 1–25. doi:10.1145/3627706

Kritikos, J., Tzannetos, G., Zoitaki, C., Poulopoulou, S., and Koutsouris, D. (2019). Anxiety detection from electrodermal activity sensor with movement interaction during virtual reality simulation. International IEEE/EMBS Conference on Neural Engineering, NER 2019-March, 571–576. doi:10.1109/NER.2019.8717170

Lui, T. W., and Goel, L. (2022). Learning effectiveness of 3D virtual reality in hospitality training: a situated cognitive perspective. *J. Hosp. Tour. Technol.* 13, 441–460. doi:10.1108/JHTT-03-2021-0091/FULL/XML

Ma, J., Jaradat, R., Ashour, O., Hamilton, M., Jones, P., and Dayarathna, V. L. (2019). Efficacy investigation of virtual reality teaching module in manufacturing system design course. *J. Mech. Des.* 141, 012002. doi:10.1115/1.4041428/367791

Makransky, G., and Petersen, G. B. (2021). The cognitive affective model of immersive learning (CAMIL): a theoretical research-based model of learning in immersive virtual reality. *Educ. Psychol. Rev.* 33 (4), 937–958. doi:10.1007/s10648-020-09586-2

Mayer, R. E., Makransky, G., and Parong, J. (2023). The promise and pitfalls of learning in immersive virtual reality. *Int. J. Hum. Comput. Interact.* 39, 2229–2238. doi:10.1080/10447318.2022.2108563

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., and Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: a meta-analysis. *Comput. Educ.* 70, 29–40. doi:10.1016/J.COMPEDU.2013.07.033

Meyer, O. A., Omdahl, M. K., and Makransky, G. (2019). Investigating the effect of pre-training when learning through immersive virtual reality and video: a media and methods experiment. *Comput. Edu.* 140, 103603. doi:10.1016/j.compedu.2019.103603

Miguel-Alonso, I., Checa, D., Guillen-Sanz, H., and Bustillo, A. (2024). Evaluation of the novelty effect in immersive virtual reality learning experiences. *Virtual Real* 28, 27. doi:10.1007/s10055-023-00926-5

Oberhauser, M., and Dreyer, D. (2017). A virtual reality flight simulator for human factors engineering. *Cogn. Technol. Work* 19, 263–277. doi:10.1007/S10111-017-0421-7/METRICS

Patrão, B., Pedro, S., and Menezes, P. (2020). "How to deal with motion sickness in virtual reality," in *Communities and Collections, 22o Encontro Português de Computação Gráfica e Interação*, 40–46.

Pennington, E., Hafer, R., Nistler, E., Seech, T., and Tossell, C. (2019). "Integration of advanced technology in initial flight training," in 2019 Systems and Information Engineering Design Symposium (SIEDS). Charlottesville, VA, 1–5. doi:10.1109/SIEDS.2019.8735628

Rasheed, F., Prasad, O., and Marisha, N. (2015). "Immersive virtual reality to enhance the spatial awareness of students," in Proceedings of the 7th Indian conference on human-computer interaction.

Rebelo, F., Noriega, P., Duarte, E., and Soares, M. (2012). Using virtual reality to assess user experience. *Hum. Factors* 54, 964–982. doi:10.1177/0018720812465006

Ross, G., and Gilbey, A. (2023). Extended reality (xR) flight simulators as an adjunct to traditional flight training methods: a scoping review. *CEAS Aeronaut. J.* 14, 799–815. doi:10.1007/S13272-023-00688-5/FIGURES/1

Shui, L., Wang, F., and Wei, Z. (2023). "Review on the applications of virtual reality in civil aviation," in *ICBAR '23: Proceedings of the 2023 3rd International Conference on Big Data, Artificial Intelligence and Risk Management* (Assoc for Comp Mach), 615–619. doi:10.1145/3656766.3656869

Sichterman, B., van Ginkel, S., van Halteren, M., Van Tilborg, R., and Noroozi, O. (2023). The effects of a constructively aligned virtual reality setting on professionals' knowledge, motivation and perceptions. *Int. J. Tech. Educ.* 6, 561–582. doi:10.46328/IJTE.462

Šikl, R., Brücknerová, K., Švedová, H., Děchtěrenko, F., Ugwitz, P., Chmelík, J., et al. (2024). Who benefits and who doesn't in virtual reality learning: an experimental study comparing two types of school. *J. Comput. Assist. Learn.* 40, 1591–1604. doi:10.1111/JCAL.12973

Slavova, Y., and Mu, M. (2018). "A comparative study of the learning outcomes and experience of VR in education," in 25th IEEE conference on virtual reality and 3D user interfaces, VR 2018 - proceedings, 685–686. doi:10.1109/VR.2018.8446486

Somerville, A., Joiner, K., Lynar, T., and Wild, G. (2025). Applications of extended reality in pilot flight simulator training: a systematic review with meta-analysis. *Vis. Comput. Ind. Biomed. Art.* 8, 25. doi:10.1186/s42492-025-00206-w

Sweller, J., Ayres, P., and Kalyuga, S. (2011). *Cognitive load theory*. Springer. doi:10.1007/978-1-4419-8126-4

Tesch, A. (2016). Implementing pre-post test designs in higher education evaluations. *New. Dir. Eval.* 151, 85–96. doi:10.1002/EV.20195

Vallès-Català, T., and Guerrero, I. (2025). Comparing arousal and workload during an emergency landing in a virtual reality and a conventional flight simulator. *Int. J. Hum. Comput. Interact.* 41, 1–13. doi:10.1080/10447318.2025.2474464

van Weelden, E., Alimardani, M., Wiltshire, T. J., and Louwerse, M. M. (2021). "Advancing the adoption of virtual reality and neurotechnology to improve flight training," in Proceedings of the 2021 IEEE 2nd International Conference on Human-Machine Systems, (ICHMS), Magdeburg, Germany, 1–4. doi:10.1109/ICHMS53169.2021.9582658

Vats, S., and Joshi, R. (2024). "The impact of virtual reality in education: a comprehensive research study," in *Transfer, Diffusion and Adoption of Next-Generation Digital Technologies TDIT 2023 IFIP Advances in Information and Communication Technology* (Springer), 699, 126–136. doi:10.1007/978-3-031-50204-0_11

Williams, K. W., Christopher, B., Drechsler, G., Pruchnicki, S., Rogers, J. A., Silverman, E., et al. (2014). *Aviation human-in-the-loop simulation studies: experimental planning, design, and data management*. United States. Office of Aerosp Med. Civil Aerospace Medical Institute; San Jose State University; Ames Research Center. Available online at: https://rosap.ntl.bts.gov/view/dot/26968.

Xiaoning, X., Yunus, M. M., and Rafiq, K. R. M. (2024). Use of VR in higher education: a systematic review (2014-2023). *Int. J. Acad. Res. Prog. Educ. Dev.* 13, 1765–1783. doi:10.6007/IJARPED/v13-i1/20659

Young, G. W., Stehle, S., Walsh, B. Y., and Tiri, E. (2020). Exploring virtual reality in the higher education classroom: using VR to build knowledge and understanding. *J Univ Comp Sci* 26 (8), 904–928. doi:10.3897/jucs.2020.049

Zhang, M., Wang, M., Feng, H., Liu, X., Zhai, L., Xu, X., et al. (2023). Pilots' spatial visualization ability assessment based on virtual reality. *Aerosp. Med. Hum. Perform.* 94, 42–428. doi:10.3357/AMHP.6198.2023

Ziakkas, D., Flores, A. D. C., and Suckow, M. W. (2023). "Human factors in aviation and artificial systems: the purdue aviation virtual reality case study," in *Intelligent human systems integration (IHSI 2023): integrating people and intelligent systems* T. Ahram, W. Karwowski, and P. Di Bucchianico (AHFE International, United States). doi:10.54941/ahfe1002864