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RESEARCH ARTICLE

An Iterative Design Method for Advancing Air Traffic Control and Management Training Through Immersive VFR 3D Map Visualization

Rafael N.C. Patrick[a]*, Tony Lee[a], Zach Desmit[b] and Nathanyal Carter[c]

[a]Grado Department of Industrial and Systems Engineering, College of Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA; [b]Northrop Grumman Corporation, Corporate, Falls Church, VA, USA; [c]The Bradley Department of Electrical and Computer Engineering, College of Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

OCCUPATIONAL APPLICATIONS

Innovative tools that align with modern learners' preferences are essential for training in safety-critical professions like Air Traffic Control/Management. This study evaluated a Virtual Reality Visual Flight Rules 3D Map Visualization Tool designed to meet the Federal Aviation Administration's (FAA) modernization goals. The tool immerses trainee in contextually accurate environments, enhancing engagement and self-paced learning. Most subject-matter experts favored 3D learning over traditional approaches, while commenting on potential integration into collegiate and FAA programs to support preparedness. Future research should explore scalability, long-term performance impact, and AI enhancements for personalized training and accessibility. This innovation bridges generational gaps in learning preferences and addresses the timely demand for well-trained certified professional controllers, highlighting the value of accessible self-paced customized training. A contextually accurate, cost-effective training system could improve knowledge acquisition and enable trainees to study beyond traditional classrooms, supporting rapid decision-making and self-efficacy – marking a step forward in occupational training.

TECHNICAL ABSTRACT

Background: Rigorous training is essential in air traffic control/management due to its dynamic, mentally-demanding, and safety-critical nature. Despite the increasing need for certified professional controllers, the Federal Aviation Administration (FAA) projects a loss of 8,595 controllers between 2021 and 2030. Low trainee self-efficacy, particularly in mastering aeronautical maps, could be a contributing factor.
Purpose: We assessed the usability and potential of a Virtual Reality Visual Flight Rules (VFR) 3D Map Visualization Tool for contextually accurate, accessible air traffic control/management training.
Method: An iterative design methodology was used to develop and evaluate the VFR 3D Map Visualization Tool with expert aviation populations. Usability was assessed using the System Usability Scale. A mixed-method approach, including quantitative Likert-scale surveys, qualitative semi-structured interviews, and open-ended questionnaires, captured feedback from subject matter experts (SMEs).
Results: The tool received positive feedback from SMEs, including certified professional controllers and aviation professionals. It achieved a mean score of 85, indicating "Good" usability, above the common industry standard. SMEs highlighted the tool's utility as an effective, accessible training tool and its potential for recommendation in collegiate training programs and FAA academies.
Conclusion: Our results accentuate the importance of modernizing training programs to align with future generations' learning preferences. The iterative design process incorporated critical SME feedback, enhancing the tool's development. SMEs preferred 3D learning over the traditional method, suggesting that as the tool develops it could improve training experiences and support rapid decision-making and increased self-efficacy. Future research would benefit from exploring performance metric comparisons between training modalities, long-term impacts, scalability, and AI integration for personalized learning in dynamic environments.

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CONTACT Rafael N.C. Patrick rncp@vt.edu Grado Department of Industrial and Systems Engineering, College of Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA.

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1. Introduction

As young people enter the workforce and retirees transition out, it's crucial to recognize that each generation brings unique challenges and needs in terms of training. These challenges remain true in professions such as air traffic control/management (ATC/ATM), where candidates undergo rigorous training—spanning from six months to five years, depending on the individual's experience and assigned roles—to adeptly navigate the dynamic, mentally demanding, and highly stressful nature of a safety-critical occupational environment and achieve recognition as a certified professional controller (CPC). In 2015, the total number of CPCs employed by the Federal Aviation Administration (FAA) dropped to 10,833—a 27-year historic low—with approximately one-third eligible for retirement (National Air Traffic Controllers Association, 2018). Despite the demand for CPCs, the FAA projects a total loss of 8,595 controllers over the next 10 years (2021—2030; Federal Aviation Administration, 2021). Considering the process of becoming a CPC, projected FAA academy attrition rates suggest that training is challenging and needs intervention. One of many reasons could be low trainee self-efficacy in the early stages of training within a new organization and social structure (Bandura, 1982; Jones, 1986; Pajares and Schunk, 2002; Van Maanen and Schein, 1977) associated with developing learning techniques for studying two-dimensional Visual Flight Rules (VFR) maps (VFR Charts, 2018; FAA, 2023) to absorb a multitude of variables (e.g., altitudes, routes, radio frequencies, airport identifiers; see Appendix A & B in Supplemental Material). The FAA recognizes a need to modernize how they train employees by incorporating new techniques and technologies for learning (Federal Aviation Administration, 2021). The timely demand for well-trained CPCs highlights the value of accessible remote training tools for increasing self-efficacy and the need for novel yet effective training methods to address antiquated industry resources.

Many educational domains that require similar cognitive responsibilities to that of the ATC/ATM environment have begun utilizing immersive technologies to aid in some aspects of training (Dawley & Dede, 2014; Makransky et al., 2019b; 2019c; Parong & Mayer, 2018; Standen & Brown, 2006; van Ginkel et al., 2019). The increasing availability of commercially accessible head-mounted displays (HMDs) has led to greater accessibility of virtual reality (VR) applications for education and training among the wider populace (Buttussi & Chittaro, 2018). Experts anticipate a widespread integration of VR technology into classrooms in the coming years (Adams Becker et al., 2017). The affordability of a portable yet high-fidelity training module to grasp contextually specific airspace information would be invaluable toward reducing "wash-out rates." A virtual 3D representation of the airspace, created using a cost-effective commercially available VR system, could improve knowledge acquisition and enable trainees to study beyond the confines of the traditional on-site ATC/ATM classroom or lab. Since VR allows learners to practice skills in simulated hazardous situations within a risk-free environment (Tichon & Burgess-Limerick, 2011), it is suitable for all aspects of training, particularly aviation safety training (Buttussi & Chittaro, 2018; Chittaro & Buttussi, 2015). In sum, VR facilitates understanding and increased confidence associated with complex concepts and procedures through observation, imitation, and participation (Goodyear & Retalis, 2010).

Given the safety-critical and technologically-hesitant nature of the ATC/ATM domain, it is crucial to collect first-hand impressions from aviation subject matter experts (SMEs) regarding novel technologies capable of providing contextually accurate supplemental remote training. Furthermore, grasping the potential applications and assessing the current state of the technology to address shifting demands and dynamic workplace conditions is crucial for ongoing development and eventual operational integration. In the study reported here, we deployed a VR-based VFR 3D Map Visualization Tool to SMEs classified as CPCs and non-CPCs with relevant training (see Section 3.1) to assess, using the System Usability Scale (SUS) and inquiry, its usability state and potential efficacy as a dependable training tool for ATC/ATM VFR Map Visualization. The VR-based VFR 3D Map Visualization Tool was expected to demonstrate satisfactory functionality with acceptable usability, usefulness, and accessibility. The tool was developed to deliver FAA-certified map training remotely, catering to both novice and expert ATC/ATM professionals. Furthermore, ongoing development is expected to lead to a capable, cost-effective training tool for improved self-efficacy through preference-based knowledge retention, transfer of training, and work readiness.

2. State of Technology

Due to the novelty of the technology and the specialized nature of the ATC/ATM domain, only a limited number of contextually relevant examples or studies were identified in the literature. However, benchmarks were drawn from industries and professions with similar occupational demands and operational environments to provide a basis for comparison (Bajaj et al., 2021; Bhagat et al., 2016; Bonde et al., 2014; Chittaro & Buttussi, 2015; Dewey, 1913; Feng et al., 2018; Hsu, 2010; Huang et al., 2010; Lim & Jung, 2013; Makransky et al., 2019a; 2019b; 2019c; McComas et al., 2002; Merchant et al., 2014; Parong & Mayer, 2018; Renninger & Hidi, 2015; Rose et al., 2000; Smetana & Bell, 2012; Smith & Ericson, 2009; van Ginkel et al., 2019). These studies align with the safety-critical challenges faced in the ATC/ATM domain, where the demanding and stressful nature of training necessitates innovative approaches to increase self-efficacy to maintain candidate interest and allow for self-paced performance training. There was a specific emphasis relevant to the intricate requirements of training to contextualize 3D artifacts and their complexities in a short training period.

It is important to note that applications of both augmented and virtual reality (i.e., eXtended reality) are limited across industries. Although, an industry that has benefited significantly from the application of eXtended reality has been manufacturing. According to Jeelani (2023), eXtended reality applications are transforming the manufacturing industry while highlighting use cases that have been seen across the industry to improve manufacturing processes, reduce downtime, and drive out defects. When viewed with a larger cross-industry lens, applications of eXtended reality are scarce. Liao and Iliadis (2021) referenced Gartner's classic hype cycle, placing augmented and mixed reality in the "Trough of Disillusionment," a phase in technology adoption where interest begins to wane after initial hype and expectations. As these technologies mature, entering the "Slope of Enlightenment," their potential benefits for enterprises become clearer, prompting increased pilot studies and cautious interest from conservative firms.

2.1. Perceived Self-Efficacy in Training

Many industries require workers to rapidly develop job-related skills and complete tasks efficiently. Due to the fast-paced nature of training, learners often experience uncertainty about their ability to succeed in performance-based tasks. This uncertainty leads to lowered perceived self-efficacy among workers, which in turn decreases workplace efficiency (Bandura, 1977; Holbrook, 2012; Zimmerman, 2000). Perceived self-efficacy refers to an individual's belief in their capability to successfully perform a specific task. This belief not only affects performance in the task at hand but also influences the individual's ability to perform other tasks (Bandura, 1997; Holbrook, 2012). Perceived self-efficacy is not about the number of skills one possesses but what one believes one can achieve with those skills in various circumstances. Individuals with low self-efficacy doubt their abilities to perform well in given situations and achieve expected outcomes—often exhibiting low motivation, diminished skills, weak commitment, and halfhearted efforts toward performance-based goals (Bandura, 1997). In the context of occupational training, it is theorized that self-efficacy beliefs predict the range of career options people consider viable for themselves and influence career choices (Lent & Hackett, 1987; Bandura, 1997). In an attempt to combat "wash-out" rates in the FAA certification process, this work seeks to operationalize Bandura's suggestion that training programs should include strategies to help workers develop and improve their technical skills, thereby enhancing their self-efficacy, albeit not measured directly.

2.2. Military VR Training

The integration of VR technology into training programs is a well-explored concept, with researchers investigating its application across various domains; albeit limited within ATC/ATM. Notable instances are cost-effective interactive 3D VR systems designed and introduced specifically for military live-firing training (Bhagat et al., 2016; Lim & Jung, 2013), centered on elevating training experiences within a dynamic and high-stakes environment. The developers sought to deliver realistic immersive training testbeds—a platform for conducting rigorous, transparent, and replicable testing of scientific theories, computing tools, and new technologies—for soldiers during live firing exercises. The results of this work support the efficacy of cost-effective 3D VR systems in military training. For instance, it was noted that the "real-world firing range mode not only helps the learner to immerse in the scenario…but can, likewise, store bullet impact point records" (Bhagat et al., 2016, p. 10) suggesting that VR training—serious gaming—leads to enhanced engagement, accuracy, while also mitigating mental stress (Hsu, 2010; Lim & Jung, 2013). Additionally, Bhagat et al. (2016) observed that training results enabled instructors to develop targeted teaching strategies to address learners' weaknesses. This supports the necessity of developing training tools with contextually relevant information.

2.3. Cognitive Advantages of VR Training

There are also motivational advantages to VR training. The dynamic and engaging nature of VR aligns with interest theory, enhances trainee motivation, increases engagement, and improves knowledge retention (Dewey, 1913; Makransky et al., 2019a; Merchant et al., 2014; Renninger & Hidi, 2015; Smetana & Bell, 2012). According to findings where the use of VR and traditional training methods were compared, immersive VR typically led to positive learning outcomes by eliciting enjoyment and motivating learners to exert more effort to make sense of the material (Bonde et al., 2014; Chittaro & Buttussi, 2015; Huang et al., 2010; Makransky et al., 2019a; 2019c; Parong & Mayer, 2018). Additionally, 3D spatial representations and interactive scenarios were found to contribute to more realistic and effective learning experiences leading to cognitive advantages—memory retention and spatial cognition (Feng et al., 2018; Makransky et al., 2019b; McComas et al., 2002; Rose et al., 2000; Smith & Ericson, 2009; van Ginkel et al., 2019). These benefits reinforce the importance of creating tools that allow users to easily simulate scenarios at home, which might otherwise be too hazardous or expensive to enact in real life, thereby enhancing self-efficacy.

2.4. VFR 3D Map Visualization Tool Development

As a foundation for the current work, an earlier iteration of the VFR 3D Map Visualization Tool (Phase I) utilized semi-structured interviews conducted with SMEs (i.e., two immersive environment specialists, an ATC/ATM training specialist, and several CPCs) to better understand the use case potential, user needs, and design requirements for developing an effective ATC/ATM training tool (Bajaj et al., 2021). CPCs reported frustrating experiences with map memorization techniques in early FAA Academy training, noting that it is a tedious process that requires a lot of long-term memorizations within a short period. Thus, the researchers determined that VFR sectional map training would be the ideal point of entry for immersive technology integration. Although augmented reality approaches were suggested, technical and operational environment limitations made it apparent that VR would be more cost-effective and accessible. In support, the immersive environment SME noted that VR would be most suitable for spatial cognition and is more capable of handling map scaling.

With these insights, we developed—in a previous Phase II (Bajaj et al., 2021)—the VR-based VFR 3D Map Visualization Tool (Figure 1) within an open-source 3D modeling software (Blender) and game engine (Unreal Engine 4) based on a published FAA En Route Qualification Training VFR Sectional Map (see Appendix A in Supplemental Material). The interface was displayed using an Oculus Quest 2 HMD to provide an accessible training option for ATC/ATM trainees. The tool is an interactive graphical user interface (GUI) that displays a 3D sectional map, allowing users to toggle on and off attributes (i.e., airspaces, victors, intersections, airports, NAVAIDS, and map), which enables the memorization of airspace elements in a self-paced digestible format. Once developed, we tested the VFR 3D Map Visualization Tool's general functionality and user-friendliness (Bajaj et al., 2021). Preliminary usability testing, using the SUS with a novice population, indicated that the VFR 3D Map Visualization Tool was user-friendly but could benefit from technical adjustments, including incorporating a training/instructional component, integrating a search bar, introducing a map legend, enhancing text size, and employing brighter and more user-friendly colors on the map. In response, the tool was further developed and retested in Phase III (*subsequent sections*).

3. Method

An iterative design methodology was used to develop a VFR 3D Map Visualization Tool for accessible ATC/ATM training as a contextually accurate remote training tool for pre-CPC and CPC populations. The subsequent sections detail Phase III development and iterative user testing with CPCs and aviation experts.

3.1. Participants

Expert users were recruited by re-engaging with participants from Phase I and Phase II interviews and establishing a network of ATC/ATM instructors at an

Figure 1. (a) Unreal Engine Development; (b) Close-up of the Toggle Settings in VR; (c) VFR Map GUI in VR.

aviation-focused university. Individuals were solicited *via* "SME Solicitation Email" and asked to participate voluntarily in Phase III of the project. The solicitation consisted of an initial prescreening using the "SME Qualification Survey" (see Appendix C in Supplemental Material) and, if qualified, continued to the "SME Exploration Survey" (see Appendix D in Supplemental Material), which began with an "Information Sheet." The prescreening consisted of eight questions which yielded 82 attempts (26.8% completion), with 35 respondents deemed unqualified due to the lack of formal ATC/ATM training or research and 21 respondents deemed qualified based on formal ATC/ATM training and/or FAA-recognized certifications. All 21 qualified respondents gained access, with 16 (11 males and 5 females) completing the "SME Exploration Survey." Respondents were aged 19 to 24 ($n=9$, 56.3%) or older than 35 years ($n=6$, 37.5%), with one individual ($n=1$, 6.3%) being between 25 and 29. The mean time to survey completion was 18 min.

Upon completion of the "SME Exploration Survey," those who indicated an interest in participating further were invited to the remote usability portion of the study, which consisted of an at-home tool assessment, "Post Usability Survey" (see Appendix E in Supplemental Material), and "Post Usability Semi-Structured Interview" (see Appendix F in Supplemental Material). Based on schedule alignment, seven ($n=7$) participants were chosen to engage in remote usability testing of the prototype VFR 3D Map Visualization Tool. This sample size was deemed sufficient given their expertise and the application of usability heuristics, which suggest that five expert users can uncover 85% of usability issues (Nielsen & Landauer, 1993; Nielsen, 2000). Regarding the population's expertise, two reported having FAA certifications for over 15 years, three reported ATM degrees, one reported being a current student pursuing a degree in ATM from an aviation-focused university, and the last reported being an aviation professor and director of training for an FAA contractor for over 12 years. Qualified participants were compensated with a digital gift card for their time and efforts upon completion.

3.2. Study Design

We employed a between-subjects, mixed-method, iterative design approach to develop an accessible and effective ATC/ATM training tool. This approach directly assessed the usability and potential of a VFR 3D Map Visualization Tool as a reliable solution for remote training. Tool iteration (GUI design) was the independent variable, consisting of two levels (Phase II and Phase III), with scores from the System Usability Scale (SUS; Brooke, 1996) as the dependent variable. Furthermore, open-ended survey questions, think-aloud data, and interview feedback were dependent measures of usability and operational potential. Once qualified *via* the "SME Qualification Survey," participants completed the "SME Exploration Survey" which collected demographic information, VR familiarity, tool impression, and projected tool utility. Thereafter, selected participants engaged in the remote usability study comprising an at-home procedural task analysis with a think-aloud protocol and a "Post Usability Survey" consisting of ten SUS 5-point Likert scale questions (Brooke, 1996; 2013; Lewis & Sauro, 2018) and design recommendations. SUS scores were calculated by determining each item's score contribution ranging from 0 to 4. For positively worded items (odd numbers), the score contribution is the scale position minus 1. For negatively worded items (even numbers), the score contribution is five minus the scale position. The final SUS score is determined by multiplying the sum of the item score contributions by 2.5, which produces a score that can range from 0 (very poor perceived usability) to 100 (excellent perceived usability) in 2.5-point increments (Sauro & Lewis, 2016). When interpreting scores, a score of 68 is considered "Average," and a score of 80 or above is considered "Good" and a common industry benchmark (Lewis & Sauro, 2018). Lastly, a "Post Usability Semi-Structured Interview," facilitated *via* Zoom, gathered qualitative responses about overall impressions and suggested design improvements. Interviews took place within 24 hours after the remote usability test, except for one participant, who was completed within two weeks. All research activities, from "SME Qualification Surveys" to "Post Usability Semi-Structured Interviews," were completed within three months and were approved by the Virginia Tech Institutional Review Board (IRB #22-847).

3.3. Materials

Research equipment included participants' mobile phones or computers for completing online surveys administered through QuestionPro. For the remote usability testing, SMEs were shipped a kit (Figure 2a). The kit included an Oculus Quest 2 HMD (controllers, batteries/chargers, and an Oculus link cable) and an Alienware Model P45E (Specs: Intel Core i7-10750H 10th Gen, 16GB DDR4, Nvidia GeForce RTX 2070 8GB GDDR6, and Windows 10 Home) capable of running the VR-based VFR 3D Map Visualization

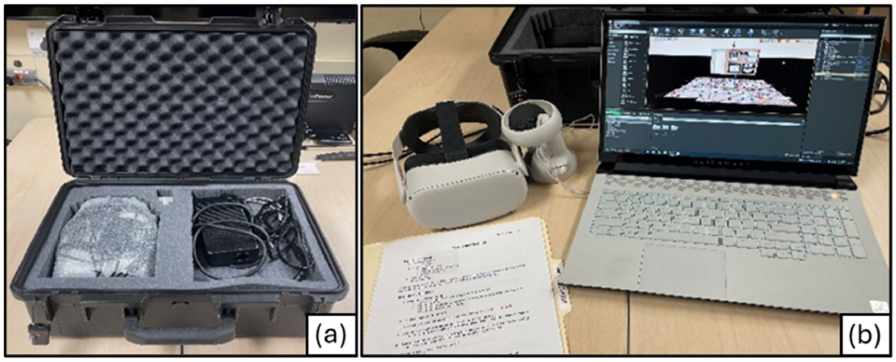

Figure 2. (a) Remote VFR 3D Map Visualization Tool in a shipping container; (b) Remote VFR 3D Map Visualization Tool Testing Setup.

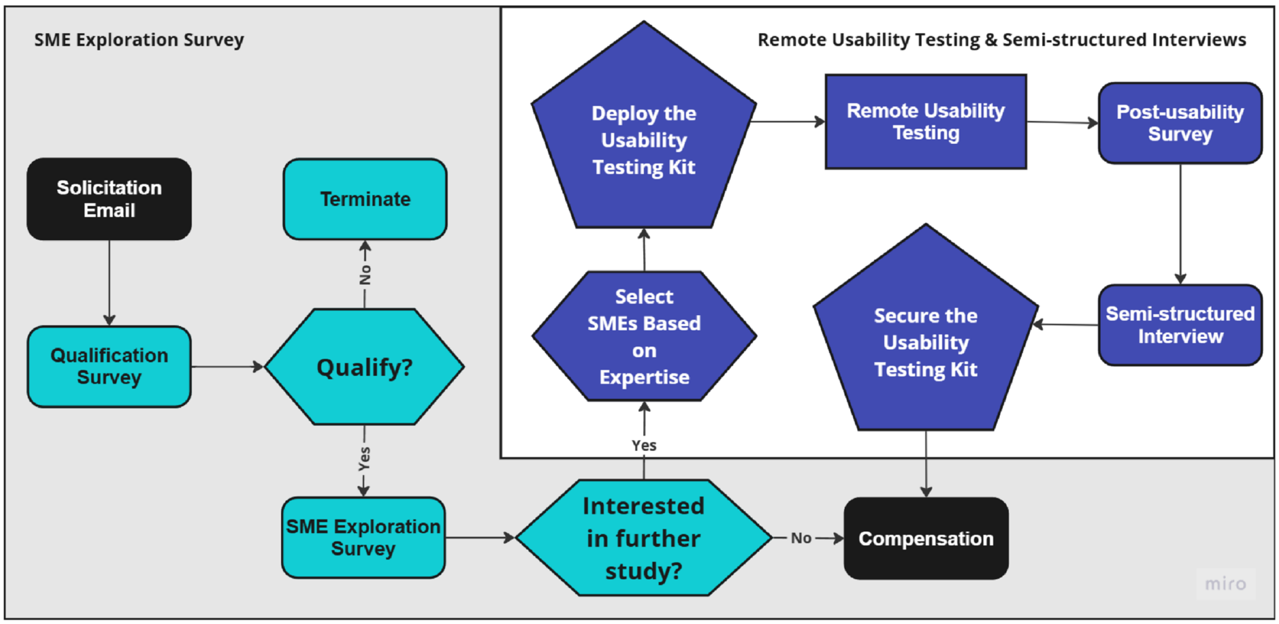

Figure 3. Experimental flow diagram.

Tool on Unreal Engine 4. A physical copy of the procedural task analysis, instructions on how to connect the VR headset to the Alienware laptop, and steps on how to launch the VFR 3D Map Visualization Tool were also included in the kit. Note: see Section 2.4 and Bajaj et al. (2021) for interface development and tool features.

3.4. Procedure

Figure 3 illustrates the protocol from solicitation to compensation, emphasizing remote usability testing and the subsequent "Post Usability Survey" and "Post Usability Semi-Structured Interview." To begin, an "SME Solicitation Email" containing a link to the "SME Qualification Survey" was shared with supporting facilitators and participants from previous phases. Those who met the criteria (see Section 3.1) were invited to complete the "SME Exploration Survey" (Appendix D in Supplemental Material) but were prompted to read an "Information Sheet" and provide consent by selecting "Yes" to continue. Thereafter, they were presented with demographic and VR experience questionnaires. The next section of the survey displayed a four-minute VFR 3D Map Visualization Tool demonstration video showcasing the functionality of the training environment. Before watching the video, participants were prompted to express their familiarity with VR and indicate their impression of the integration of immersive technology into the ATC/ATM domain and its potential in the training program. After watching the demo video, participants were asked to provide feedback (Table 1) and provide recommendations on how to improve the tool. Then,

Table 1. VFR 3D map visualization tool demo video questionnaire.

Count	Question
1	Are there any domain specific elements missing from the VFR 3D Map Visualization Tool?
2	On a scale of 1 to 5, how much technical support do you think you would need to be able to use this system?
3	On a scale of 1 to 5, how likely are you to use VFR 3D Map Visualization Tool for training?
4	On a scale of 1 to 5, rate its effectiveness as a training tool.
5	What changes or modifications would you like to see in the tool?
6	Based on the improvements you mentioned above, on a scale of 1 to 5, rate the tool's effectiveness.
7	Would you recommend using this tool in a classroom setting?
7.5	Why or why not?
8	Would you rather utilize this 3D learning tool or continue using the original 2D teaching methods?
8.5	Why or why not?

participants were asked to indicate their interest in an at-home remote usability test of the training tool, a post-usability survey, and an interview for additional compensation.

Once a participant was selected to engage in the "Remote Usability Testing & Semi-structured Interview," a timeline was established, and the remote usability kit (Figure 2a) was deployed to users' preferred addresses with step-by-step instructions for completing the study (Figure 2b). Participants were instructed to contact the research team once the package arrived to schedule the "Semi-structured Interview" and to obtain the access code for the kit. The interview, administered over Zoom, was scheduled no later than 48 hours after the kit's arrival, although participants were granted a maximum of 2 weeks to complete the study. Participants completed a series of procedural tasks (outlined in Table 2 and shown in Figure 1) while screen recording and verbalizing their thoughts and actions (i.e., think-aloud protocol) to provide SME-level contextual information. Upon completion, participants were prompted to provide feedback *via* the "Post-Usability Survey" (Appendix E in Supplemental Material) using a unique participant code. Once the scheduled "Semi-structured Interview" (Appendix F in Supplemental Material) was completed, participants were provided with instructions for returning the kit. Upon confirmed receipt, compensation was administered *via* QuestionPro. Thereafter, data was exported to a secure hard drive and analyzed, while Microsoft Excel was used to manually code open-ended data according to the specific questions and keywords to establish a thematic tally frequency database. Finally, the content of the kit was inspected for damage, the data was purged, and then the items of the kit were sanitized using a Cleanbox CX2 system in preparation for the next scheduled participant.

Table 2. VFR 3D map visualization tool remote SME usability tasks.

Task number	Task
1	Rotate the controls left and right, move up and down, move forward and backwards.
2	Toggle the selector off and on.
3	Point the motion controller in Grenada, MS.
4	Verify that the city and other map data variables illuminates.
5	Toggle the on/off layers menu.
6	Turn off victors, intersections, and NAVAID's.
7	Turn off ALL layers simultaneously.
8	Turn on ALL layers simultaneously.
9	Reset the camera.
10	Find and name all of the six available air spaces.
11	Locate and name five airports in the Columbus 3 MOA airspace.
12	Name four of the victor lines coming from Greenville.

4. Results

Results from the VFR 3D Map Visualization Tool at-home remote usability pre-survey, post-survey, and semi-structured interviews are reported in Table 3 and the following sections. *Note*: In Figures 4 and 5, favorable responses are indicated in blue (positive direction), and unfavorable responses are expressed in orange (negative direction).

4.1. SME Exploration Survey

Most of the feedback, reported as thematic tallies, was positive regarding SME impressions of implementing a VFR 3D Map Visualization Tool into current ATC/ATM training programs (Figure 4). Some negative comments were reported regarding the tools use in a classroom setting and preferences for 3D vs. 2D learning modalities (Figure 5).

4.2. Post-Usability Survey

When participants were asked "What would you like to see added to our software?," one recommended adding map zoom in/out functionality, two visualizations of airspace based on altitude, one place airspace map in the front, not looking down, one faster user interface feedback, one add more airport frequency information elements, one has a larger layout of the map, one includes fill in the blank exercise functions, and one includes grab and move functions. When asked "What would you like to see removed from our software?," six responded with "N/A," and one recommended removing the sun position slider as it is unimportant. Seven SUS responses were calculated (see Section 3.2) and reported in Figure 6. The lowest SUS score was 50, and the highest was 100, with the mean score being 85 out of a possible 100. Ultimately, the tool surpassed the "Good" threshold for usability (e.g., 80), a common industry benchmark.

Table 3. VFR 3D map visualization tool remote SME usability post-survey results.

SME exploration survey	#	% of total
Have you used a VR headset before?		
Yes	13	81.2
No	3	18.8
Total	16	100
What VR headset have you had exposure to? (Select All That Apply)		
Oculus Quest 2	9	60.0
Oculus Rift	3	20.0
Valve Index	2	13.3
PlayStation VR	1	6.7
Total	15	100
How often do you use VR?		
0–3 h a week	12	92.3
3–6 h a week	1	7.7
Total	13	100
What have you used VR for? (Select All That Apply)		
Gaming	12	70.6
Research Engagement	2	11.8
Fitness	1	5.9
Work	1	5.9
Testing Products	1	5.9
Total	17	100
5-point Likert Scale Questionnaires		
How much technical support would you require to be able to use this system? (5 – being A Lot)	3.0	60.0
How likely are you to use this prototype as a training tool? (5 – being Very Likely)	3.75	75.0
How effective is this prototype as a training tool? (5 – being Excellent)	3.63	72.6
Remote Usability Post-Survey		
Would you rather utilize this 3D learning tool or continue using the original 2D teaching methods?		
3D	11	68.8
2D	5	31.2
Total	16	100
Would you recommend using our prototype in a classroom setting?		
Yes	8	50.0
No	2	12.5
Maybe	6	37.5
Total	16	100
5-point Likert Scale Questionnaires		
How intuitive was the system?	4.43	88.6
How likely are you to recommend this application as a training/memorization tool?	4.71	94.2

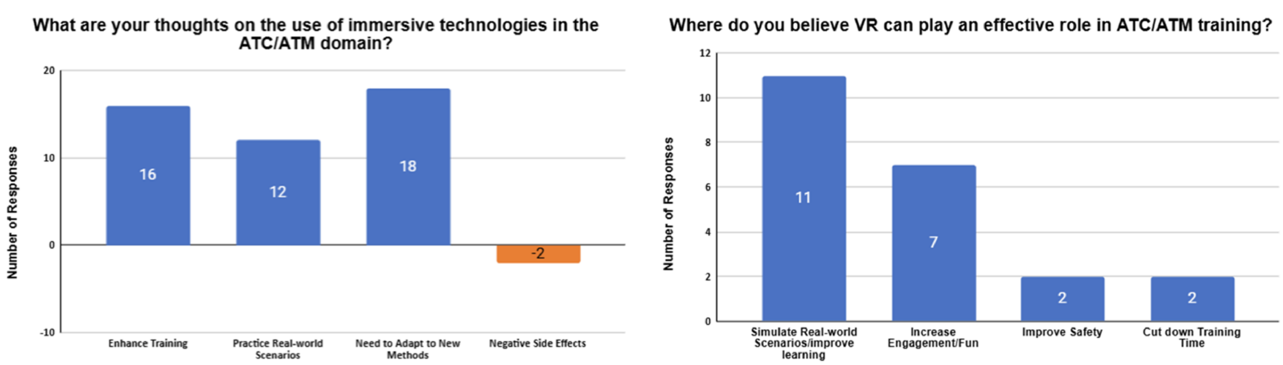

Figure 4. Feedback on the VFR 3D map visualization tool.

4.3. Semi-Structured Interviews

When asked, "What do you think of the VFR 3D Map Visualization Training Tool?," SMEs responded by expressing their satisfaction with how intuitive it was and enjoyed being able to see the map in 3D. Users appreciated how easy it was to use and particularly liked the ability to point at the map and highlight elements, as well as toggle layers "on" and "off." However, they noted some errors associated with toggling switches. When asked, "Do you think VFR 3D Map Visualization Training Tool can be widely utilized and effective in the near future upon improvements?," users suggested adding Victor airways, visibility, and invisible functionalities, incorporating games to test memorization over repetition, providing an empty map for fill-in-the-blank exercises, showing the

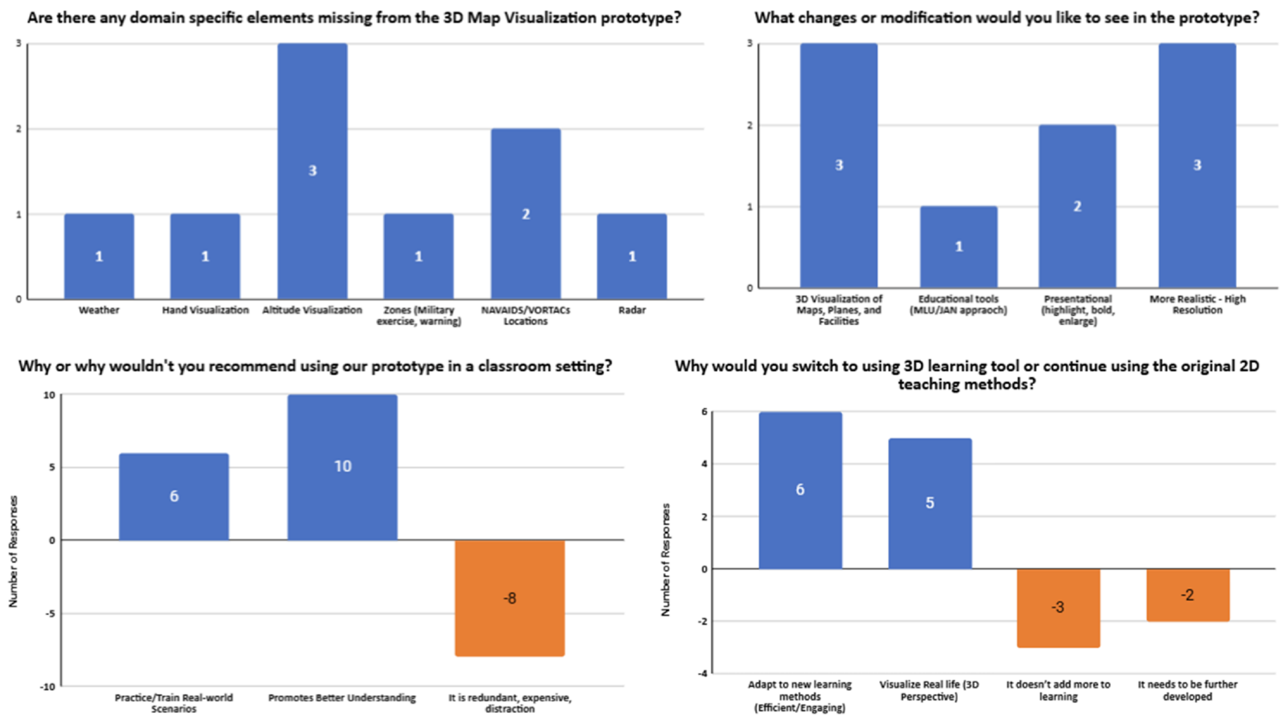

Figure 5. Qualitative responses from the SME exploration survey.

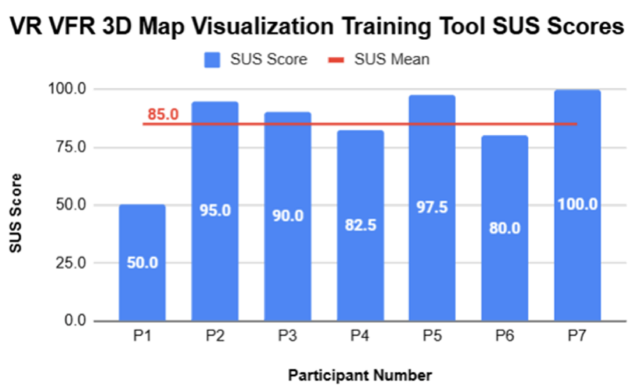

Figure 6. System usability scale (SUS) mean scores (Brooke, 1996).

elevation of different airspaces, and obstacles for visualization. They found the ability to highlight maps helpful for picking up information faster and considered it better than traditional methods due to its engaging nature. They also highlighted its potential benefits for take-off and landing operations, as well as post-training incident analysis. Users appreciated the ability to use the software at home and at any time of the day for more hands-on training but noted that while it could be integrated into academies, it would not replace traditional training methods. When asked about their feelings toward using the VR platform, users described the experience as "cool" since it promoted a different way of learning, while another noted that it makes them feel "hopeful" due to the outdated nature of current training programs. Other noteworthy responses were that it was engaging because of its interesting and easy-to-use interface, calm learning environment, and impressed by the ability to use VR headsets for immersion and manipulation. Lastly, they suggested removing unimportant elements like the sun and shadow effects and moving the map to the front instead of being underneath participants, to better reflect traditional learning formats.

The hardest part of using the tool, as reported, was getting used to the controls, remembering the location of their hands, and frustrations with having to look down at the map. Most participants struggled with hardware setup issues such as updates and linking the VR HMD with the computer. When asked about possible improvements to the tool, users suggested making the map bigger, providing more access to other maps, adding zoom-in and zoom-out features, improving user interface feedback latency, reformatting the map's position to match traditional settings, displaying altitudes of each station, incorporating tasks into the training, including tutorials on how to use the controls, and implementing a hand feature for grabbing elements and moving them for increased immersion. Finally, when asked if they had any further comments about the VR HMD or training tool that has not been mentioned, respondents expressed a desire for the tool to be downloaded onto the VR HMD instead of having to launch it manually on the computer. They also suggested features such as passthrough capabilities for environmental awareness and the ability to see both virtual and real environment elements simultaneously (i.e., augmented or mixed reality), which they believed would be beneficial.

5. Discussion

We considered aviation experts to be the ideal population for engaging in user testing of the VFR 3D Map Visualization Tool, as their involvement is critical for assessing the tool's usability and potential in an applicable context. Therefore, data collection required strict inclusion criteria for participant selection during the recruitment stage (see Section 3.1). The sample size ($N = 7$ CPCs) aligns with Nielsen's (2000) recommendation of 5—7 expert users and Tullis and Stetson (2004) recommendation of 8—12 general users for reliable SUS scores. Given the population's expertise and moderate diversity (i.e., CPCs, ATCs in training, and aviation specialists), the current sample size is justified as it ensures detailed and context-specific feedback with sufficient usability coverage of ~85%, according to Nielsen (2000). Furthermore, by combining qualitative insights with SUS scores, quantitative data can be contextualized to provide a reliable and comprehensive evaluation of the tool's usability and potential for implementation at the collegiate and higher levels of ATC/ATM training.

Our research effort was driven by the potential advantages of immersive technologies in improving training for current and future ATCs/ATMs. Given the intricate and dynamic nature of operations, the VR-based VFR 3D Map Visualization Tool demonstrated satisfactory functionality with acceptable usability, usefulness, and accessibility. The tool was developed to provide effective remote FAA-certified map training for novice and expert user populations of ATC/ATM professionals. SUS score and interview results indicate that SMEs found the VFR 3D Map Visualization Tool to be useful and capable of providing effective remote ATC/ATM training; therefore, immersive simulations could accurately replicate real-world scenarios (i.e., VFR sectional maps), leading to higher self-efficacy through better skill acquisition and performance, and potentially reducing dropout rates at the FAA academy level. Furthermore, results from SUS scores, surveys, and interview data were consistent with existing research in applied human factors and occupational ergonomics (Bhagat et al., 2016; Buttussi & Chittaro, 2018; Chittaro & Buttussi, 2015; Dawley & Dede, 2014; Dewey, 1913; Feng et al., 2018; Hsu, 2010; Huang et al., 2010; Lim & Jung, 2013; Makransky et al., 2019a; 2019b; 2019c; McComas et al., 2002; Merchant et al., 2014; Parong & Mayer, 2018; Renninger & Hidi, 2015; Rose et al., 2000; Smetana & Bell, 2012; Standen & Brown, 2006; Tichon & Burgess-Limerick, 2011; van Ginkel et al., 2019) highlighting the benefits and significance of interactive and experiential learning in training contexts and, most importantly, SME involvement in iterative product design. SMEs in our study indicated that the tool leads to enhanced engagement while repeated use could lead to training transfer to real-world settings—which is an indication of improved self-efficacy. In sum, CPCs expressed positive and encouraging impressions of the VFR 3D Map Visualization Tool. Furthermore, the value of SME involvement throughout development was reinforced as an essential component for implementation in the intended operational environment.

5.1. Training and Tool Usefulness

In terms of overall usefulness, SMEs in this study reported a mean of 3.0 out of 5 concerning training and support needs to properly and effectively use the VFR 3D Map Visualization Tool while also reporting a mean score of 4.43 out of 5 in terms of intuitiveness. Qualitative and quantitative results indicated that further development is necessary, however, since SMEs evaluated the tool first-hand, this indicates that tutorials are required beyond basic occupational knowledge. Such training could be due to the novelty of VR in general and/or the complex nature of replacing traditional 2D training with 3D VR. On the other hand, results indicate a favorable level of technology acceptance due to reports that 50% of the SMEs indicated that they would recommend using the tool in a collegiate and/or FAA academy classroom settings, and when asked how likely they are to recommend this tool, the mean response was 4.71 out of 5. In terms of accessibility, the VFR 3D Map Visualization Tool was deployed and utilized by an expert population with limited technical assistance, indicating that the process of remote ATC/ATM map training is feasible and cost-effective. Based on the positive perceptions and recommendations, a VFR 3D Map Visualization Tool has the potential to support what the FAA states as a need to modernize and incorporate new technologies and techniques for training future CPCs.

5.2. Iterative Development

During an earlier stage of development (Phase II), initial user testing was conducted with a novice non-aviation population. The prototype was assessed based on a set of similar usability tasks where the mean SUS score was 73.2, which was deemed "Average" in terms of usability (Bangor et al., 2009; Lewis & Sauro, 2018). The tool was then updated based on feedback (see Section 2.4), and then a second round of user testing was performed remotely (to also assess accessibility) using an expert population of CPCs, CPCs in training, and aviation professionals (see Section 3.1). The resulting SUS scores produced a mean of 85, which was considered "Good" in terms of usability, indicating effective improvements. Despite its "Good" usability rating, the VFR 3D Map Visualization Tool would benefit from continued development based on Phase III SME recommendations and then re-evaluated using a diverse CPC population toward the production of an intuitive, contextually accurate, reliable, and accessible ATC/ATM training tool (see Section 5.3).

5.3. Tool Recommendations

Based on qualitative feedback, most CPCs expressed a positive attitude toward integrating VR technology into ATC/ATM training programs. SMEs emphasized its potential to enhance self-efficacy by replicating real-world scenarios, improving understanding and perspective, and increasing engagement and enjoyment. They also noted that VR technology could reduce training time and improve accessibility. Conversely, some SMEs expressed concerns about the cost of implementation, its distraction potential, redundant content, simulation sickness, and technical limitations of immersive technologies. Nonetheless, recommendations on how to improve the tool were provided. First, several mentioned the addition of altitude visualization on the map since the current iteration displays 2D elements on a 3D layout. Future iterations would benefit from the display of realistic and spatialized elements (i.e., visual representation of different altitudes in planes, models of planes, facilities, mountains, and especially victor airways). Second, SMEs reported the desire for navigational aids (NAVAIDS) and VHF Omni-directional Range/Tactical Air Navigation (VORTACs) locations since this information is critical to daily operations and necessary for training. Third, in terms of educational readiness, it would be useful, for instructors, to have the ability to highlight, bold, enlarge, and hide certain elements during demonstrations. Also, including other elements such as weather information, radar, and visual representation of any active zones (i.e., military exercises, warnings, etc.) would be beneficial.

5.4. Limitations

We encountered some limitations. Notably, some participants experienced simulation sickness when using the VFR 3D Map Visualization Tool for long periods. Additionally, procedural difficulties arise while switching between viewing the map through the VR HMD and physical copies of instructions. Future testing would benefit from including non-distracting procedural task instructions within the VR interface. Despite testing with an expert population, the small sample size limited the diversity of user experience within the occupational domain (i.e., tower, TRACON, and en route controllers) and VR familiarity. However, according to heuristic evaluation principles, which suggest that data from 3 to 5 expert users are sufficient for effective and generalizable design evaluation (Nielsen, 2000), the sample size is deemed acceptable at this stage of development.

Future research with larger and more diverse samples (i.e., varying levels of expertise and occupational duties), as well as objective performance measures (e.g., physiological, knowledge and retention assessment, etc.), would provide a more comprehensive understanding of immersive technology effectiveness in ATC/ATM training. Given that our study focused on the feasibility of developing and providing a VFR 3D Map Visualization Tool to aviation experts, there were time constraints in evaluating its effectiveness on trainee learnability. Therefore, future developmental efforts should collect various task-performance metrics (e.g., self-efficacy, aptitude, retention, etc.) to compare these results with those of traditional 2D learning methods.

6. Conclusion

In conclusion, each generation brings unique challenges to training in safety-critical professions like air traffic control/management, necessitating innovative approaches to meet evolving needs. Results from our study highlight the potential of a Virtual Reality Visual Flight Rules Three-Dimensional Map Visualization Tool for modernizing air traffic control/management training programs (both academic and Federal Aviation Administration), making them more accessible, enhancing self-efficacy, and improving learning outcomes. Aviation-specific subject matter experts rated the current training tool as “Good” regarding usability on the System Usability Scale, preferred the 3D training tool over traditional 2D methods, and reported a high likelihood of recommending the tool. This indicates a need for updates to collegiate and Federal Aviation Administration training programs. Lastly, recommendations to improve the tool reinforced the value of expert engagement and the iterative design process. Future research should explore the scalability of 3D visualization tools, compare them to traditional 2D methods for aptitude and retention, and incorporate AI for personalized learning. Furthermore, longitudinal studies could continue to assess 3D visualization tools’ impact on trainee performance and self-efficacy, ensuring a well-prepared future workforce.

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Conflict of Interest

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ORCID

Rafael N.C. Patrick http://orcid.org/0000-0002-7503-2184

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