An Augmented Reality Thunderstorm Simulation to Improve Aviation Weather Pilot Training

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ABSTRACT

General aviation (GA) accidents costs between 1.6 to 4.6 billion dollars annually and with 55%-85% of them credited to pilot error. Passive training material (video, text, image, etc.) rarely provide the freedom to combine various hazard and weather information simultaneously. Active in-flight training provides realistic experiences but is expensive and limits the type of weather phenomenon the students can safely experience. Military pilots experience similar issues as Air Force officials reported that it costs between 3 to 11 million dollars to train a fighter pilot. To address this problem, an Augmented Reality (AR) thunderstorm model was developed and evaluated. By utilizing AR, pilot trainees can learn about, and interact with, a three-dimensional (3D) thunderstorm in a cost-effective, accessible, and engaging environment during initial flight training.

This paper describes the design and development of an AR 3D thunderstorm model for aviation education. To ensure pilot trainees fully understand the characteristics of a thunderstorm, the model had to be dynamic, realistic, and volumetric. Particle systems were utilized for their flexibility and variation to represent a realistic thunderstorm cell with visible hazards and precipitation. To overcome the challenge of dynamically changing weather information, a specialized shader was created to display different color information based on its location in a cloud and time during the cycle. With the incorporation of the thunderstorm model into a low-cost mobile AR application, this framework provided an engaging and immersive training experience with a realistic visualization. An initial evaluation of the training tool was performed and received positive feedback while showing significant improvement in learning outcomes. This evaluation suggests that this tool could be a useful aid in training pilots about the dynamic's natures and dangers of thunderstorms during flight operations.

ABOUT THE AUTHORS

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INTRODUCTION

From 2004 to 2014, GA accounted for 6.74 accidents per 100,000 flight hours each year with 1.27 of them being fatal (Kuo et al., 2017). GA refers to all civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire (ICAO, 2009). Research into fatal weather-related GA accidents in the United States, between 1982 and 2013, reveals there were 58,687 total GA accidents in the United States. Of these, 19.3% were fatal, with a total of 20,660 fatalities. Among those accidents, 25% (15,439) were caused or contributed to by weather, including 3,972 fatal accidents and 8,052 fatalities (Fultz & Ashley, 2016).

To better address this problem, the Federal Aviation Administration (FAA) analyzed the challenges of current general aviation training. When the FAA conducted a weather knowledge test on over one thousand GA pilots, the result showed that many participants lacked weather knowledge and had difficulty recalling what they had learned. The results also showed that previous flight experience did not significantly affect a pilot's level of weather knowledge. Lastly, most of the participants did not have an accurate assessment of their own knowledge level (Burian et al., 2002). A training survey was conducted with 410 Certified Flight Instructors (CFIs) to evaluate their instruction provided to students on weather knowledge. The Friedman Test for Related Sample reported that weather-related decision-making was the most important topic for instructors ($p < .001$). However, most instructors spent more time on weather regulation topics in the actual training. The actual time spent on weather hazard education was also ranked lower than its importance. When teaching the cause of weather, instructors reported their knowledge level using a 5-point Likert scale, with 5 being extremely knowledgeable. These results ($M= 3.69$, $SD=.75$) were significantly higher than their self-reported overall instruction quality level ($M=3.33$, $SD=.95$). This suggested that most CFIs' actual instruction on weather content was either better than their other instruction or not at the mastery level reported. (Burian & Feldman, 2009). Weather hazard instruction is mostly done in a classroom setting with activities varying significantly across instructors (Brown et al., 2019; Burian & Feldman, 2009). GA accident statistics due to weather coupled with the inconsistent manner in which weather knowledge is taught to pilots, supports the notion that a problem exists.

Ortiz, et al. (2017) suggested that trainees will efficiently practice and refresh their memory on performing specific tasks if weather-related scenarios can be run in an easily accessible manner such as on a desktop computer or mobile device. However, while many current flight simulators aim to train fundamental flight techniques, few have the fidelity to adequately represent real world weather hazards. Many simulated scenarios only focus on emergency situations without weather information. Such simulations focus more on pilot operation and not decision making during weather hazards (Noh, 2020). On the other hand, currently available high fidelity flight simulators, with weather training systems, are too expensive to be easily accessible to trainees (Berendschot et al., 2018). The same problem occurs in military aviation as well. With the high fidelity simulator and training program, a fighter pilot still required approximately 5 years of training at costs ranging from 3 to 11 million dollars (GAO, 2018). Studies in education have overwhelmingly shown that relying on student's mental models to instruct on complex 3D phenomena is not as effective as using Extended Reality (XR)-enabled simulations. Specifically, for pilot education, research suggests that access to realistic 3D weather environments in initial flight training can greatly enhance teaching and learning outcomes (Pennington et al., 2019).

To overcome the above challenges in aviation weather training, any new technology needs to: 1) have a realistic and immersive appearance of weather phenomena, 2) work in conjunction with traditional classroom or flight instruction materials, and 3) be easily accessible to trainees. Several XR technologies were considered for this research. For example, virtual reality (VR) is using hardware and software to create a entirely synthetic environment for a user. Everything viewed by a user, whether in a headset, computer screen, or large projection system, is computer generated. AR is a computer-mediated version of the physical world, where virtual content is overlayed on top of a real-time video feed (e.g., smart device) or on direct light rays through transparent lenses (e.g., see through head mounted display) (Lee, 2012; Billinghurst & Dünser, 2012). For this research, AR was chosen as the technology platform as it can deliver all of the aforementioned capabilities if developed and tested properly. To evaluate this solution, a 3D thunderstorm interactive model was developed. The following sections of the paper present the thunderstorm model development and its implementation in a AR mobile application along with an initial evaluation performed with GA students.

BACKGROUND

AR technology presents 3D objects overlayed on real life environments, which can be viewed on mobile devices such as smartphones or tablets. Mobile AR technology is relatively inexpensive and easy to access. Compared with passive training materials or high-fidelity simulators, it brings a new way of presenting weather phenomena. In order to test the effectiveness of using AR technology in weather training, this paper takes the thunderstorm cell cycle model as an example.

Thunderstorm Cell Cycle

All thunderstorms have conditions that are a hazard to aviation. These hazards occur in numerous combinations. While not every thunderstorm contains all hazards, it is not possible to visually determine which hazards a thunderstorm contains. Therefore, to represent a typical thunderstorm for teaching and evaluation purposes, the researchers chose to simulate a single thunderstorm cell cycle. A thunderstorm is defined as a local storm caused by a cumulonimbus cloud usually accompanied by lightning, thunder, strong wind, rain, and hail. For a thunderstorm to form, the air must have sufficient water vapor, an unstable lapse rate, and an initial upward boost (lifting). A thunderstorm lifecycle progresses through three stages: the cumulus, the mature, and the dissipating. Weather recognizable as a thunderstorm should be considered hazardous, as penetration of any thunderstorm can lead to an aircraft accident and fatalities to those on board (Brown, et al., (2021), FAA, 2013).

Current Aviation Training Material

Aviation simulators have a long history in pilot training. At the beginning of the 20th century, ground simulators were developed to simulate movement, banking, and other skills (Page, 2000). In 2011 the Scalab Virtual Reality Simulator was developed using a virtual reality (VR) head mounted display (HMD) and data gloves. This tool was integrated into an open-source simulation environment called FlightGear that could run on a standard PC, with the HMD and data gloves required (Yavrucuk et al., 2011). With the current VR simulations, simulator sickness is also a barrier that limit students' access (Geyer & Biggs, 2018). To simulate motion, hexapod platforms have also been used in flight simulators for civilian aircraft for over 40 years. For military pilots, the Dynamic Flight Simulator (DFS) has been used to fully train pilots with minimal to no training in a real aircraft (Dourado & Martin, 2013). The ability to adequately simulate weather hazards and severe weather requires high-cost full-fidelity flight simulators. Due to the cost and space of flight programs, most pilots cannot use these simulators extensively in the early stages of learning basic weather hazards.

Research has shown the importance of initial training from certified flight instructor (CFI) on weather hazards. The initial training from CFIs is one of the primary influences on a pilot's behavior when facing severe weather conditions (Burian & Feldman, 2009). However, current initial weather aviation training is mostly done using traditional material, where the weather information is presented from textbooks, images, and videos. Research has shown that limiting students' exposure to challenging weather will increase risk during actual aircraft operation (Johnson & Wiegmann, 2015). Based on research done by Ortiz et al. (2017), 2D weather information required trainees to convert it into 3D mental models. This process can be difficult for student pilot. To overcome this limitation, simulation-based training was used to as a means for students to access the training modules (Ortiz et al., 2017).

Augmented Reality Benefits for Training

AR refers to a visual technology that presents computer-generated non-physical information on top of a live real-world environment (Lee, 2012). AR might be optical as a see-through technology where a helmet or HMD allows a user to view the natural environment with virtual objects on top of it, as shown in Figure 1 (Hoover et al., 2020). On the other hand, AR can also be a video-based see-through technology. The physical environment is captured by a device camera in real-time and virtual objects are presented on top of the video, as shown in Figure 2. Video-based AR devices include smartphones, tablet or computers with a camera attached.

Figure 1. See-through AR with Microsoft HoloLens.

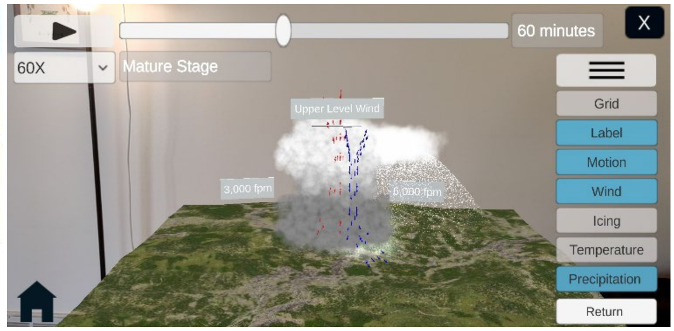

Figure 2. Video-based AR.

AR mobile applications have been successfully developed and implemented in a wide range of training areas. For example, when applied to guided assembly in manufacturing, using AR instructions is approximately 30% faster than static instructions presented on a tablet or desktop computer. (Hoover et al., 2020). In another example, an AR mobile application was developed to simulate emergency situations such as earthquake. Trainees can use this system to quickly familiarize themselves with Emergency Response Information Systems (ERIS) for emergency management. In the authors' initial analysis of this application, the AR technology showed its ability to assist trainees in getting familiar with their new mobile ERIS (Sebillo et al., 2016). The mobile AR technology is easily accessible due to the wide ownership of smartphones.

METHODOLOGY

Model Creation

The model simulates a single 60-minute thunderstorm cell cycle moving through stages of developing, mature, and dissipation. The model contains different hazards and weather information during a thunderstorm, as shown in Figure 3. Hazard and weather information including temperature, icing, wind, precipitation, and labels for wind speed can all be accessed.

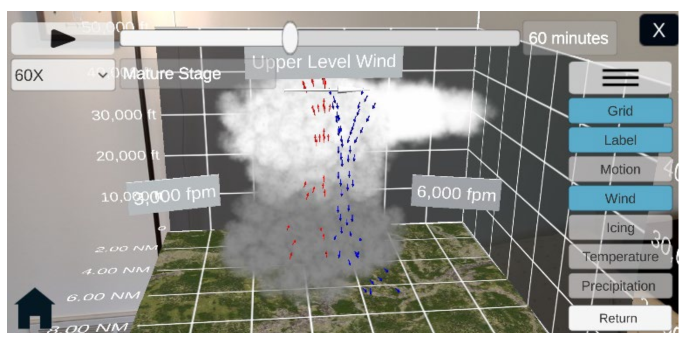

Figure 3. Control Menu for Thunderstorm Model.

The thunderstorm cycle takes place over a 60-minute period, with some hazards occurring for very short durations during this time. Thus, the simulation includes a user interface (Figure 3) that contains a play/pause button, play bar, and playback speed options to control the cloud animation during its cycle. Due to the size of a phone screen, the thunderstorm cloud is scaled to a smaller size for easy viewing. By using AR as the visual modality, a user can walk around the model with their phone or tablet to observe from different angles and distances. Implementing the grid around the cloud allows a user to gauge the actual sizes of different thunderstorm characteristics.

One such characteristic, critical to pilot training, is when a microburst forms during a thunderstorm. A microburst is an event where intense rain (i.e., virga) falls from the middle of thunderstorm without reaching the ground. The force is so great, that a dust ring, is often formed. Microbursts are very powerful, albeit short events and need to be understood and avoided by pilots when in flight. The AR model contains a detailed simulation of a microburst during its stages: 1) formation, 2) impact and 3) dissipation. A screenshot of the modeled microburst with virga and dust ring is shown in Figure 4.

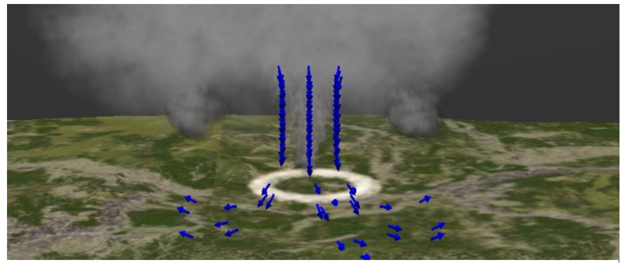

Figure 4. Microburst Characteristics.

Code Implementation

For effective use of AR, registration to align the physical and virtual environments is necessary. To ensure the position and orientation of the model, an accurate approach is to use a physical marker to establish a reference position in the physical environment. The objects are then rendered on a mobile device based on the marker's position captured by the device's camera. For this paper, the thunderstorm model was delivered through a marker-based mobile application, called WeatherXplore (L. Brown, 2019).

The AR functionality of the model was developed using Unity3D with the Vuforia plugin to enable AR functionality(Unity Technologies, n.d.). When launched, the application will turn on the system's camera to capture real-world information and check for the trigger image. It was found that the quality of trigger image will affect the recognition process and the stability of the cloud model. The team overcame this limitation by designing an image with high contrast and limited repetitive patterns to maximize tracking performance as shown in Figure 5. After triggering the thunderstorm model, the menu page is initialized. Users choose from various content to assist their learning process. The full thunderstorm cycle is available to enhance traditional classroom and textbook content. In addition, a microburst model and two learning activities are also available as these are specific conditions of a thunderstorm that are particularly dangerous for pilots when encountered. Once the model is presented in the environment, a user can view it through a smartphone or tablet from any angle and distance to visually inspect all elements. The capability of AR to naturally move in and out (analogous to zooming in and out on a desktop) promotes more interaction with the thunderstorm content.

Figure 5. WeatherXplore AR Marker

Technical Development of Physics Models

The Unity Particle System API was used to represent a realistic thunderstorm cloud model, as shown in Figure 6. The API allows particles to be emitted and their behavior controlled during their virtual lifetime. Clouds have a dynamic and "full" appearance and can be represented by a volumetric model. As a result, the particle system attached to one single cloud unit emits a total of 10 particles with random rotations between -150 to 150 degrees per second during their virtual lifetimes. Since the cloud was present during the whole simulation, particles were emitted at the start of the animation and continued while the model was running. Although thunderstorm clouds often form in similar shapes (i.e., forming an anvil type shape), there are differences from one to another. In addition, the ability to control the cloud and move it as desired for learning activities was needed. Thus, each cloud is formed by five different segments. Each segment contains particles emitted with random motions as described earlier. Although the segments are set in relation to one another, the particles within each segment can move differently. This allows each segment to be different from one another, while still maintaining high level shape characteristics. By using this modular approach, clouds can be authored much faster and be more dynamic in their structure (Figure 6). This approach significantly reduces the time to create

Figure 6. Cloud Model Developed by Particle System.

unique cloud formations (e.g., duplicating cloud segments or the entire cloud cell).

The thunderstorm model has a color distribution built-in as the density of the cloud changes based on its height and stage of the cycle. It is hard to accurately mark this change in a 3D cloud model. A self-developed shader script was developed based on factors such as height and thunderstorm stage to allow gradual color changes throughout the cloud. This shader was also extended to include icing conditions and temperatures through the cloud (Figure 7) as they have the same challenge of representing gradual color in the 3D model. Various temperature and icing conditions were represented using different symbols with reference legends to indicate the meaning of each color according to FAA guidelines.

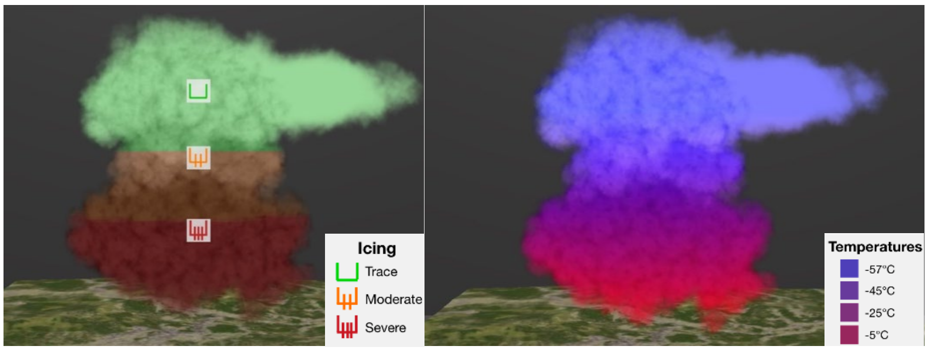

Figure 7. Icing (Left) and Temperature (Right)

There are two types of precipitation present in a typical thunderstorm cell cycle: rain and hail, each drop from a different region in the cloud. In order to achieve a realistic representation, particle systems were again used to produce these phenomena. Each drop had a gravity force attached to essentially make it fall from the cloud. Two particle systems were set to render two different materials with a different texture to simulate each precipitation type. By setting the lifetime of emitted particles, each disappears while hitting the ground or dissipating in the air to reflect an actual thunderstorm situation, as shown in Figure 8.

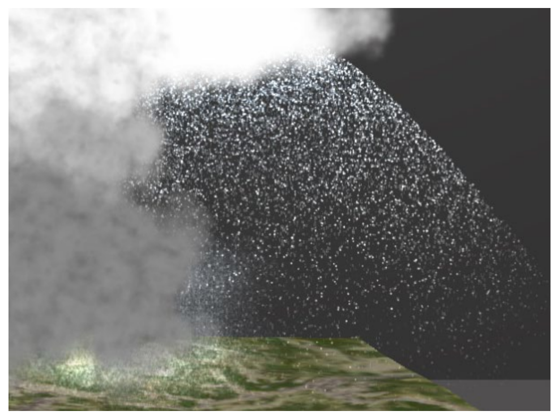

Figure 8. Thunderstorm Simulated Precipitation.

Due to the range of learning activities for which the model was designed, it was necessary to create two different viewing modes. The first is cloud-centric, which allows a trainee to view the model statically as the ground moves underneath the cloud. This effectively puts the user's viewpoint moving at the same speed as the thunderstorm and moving with it. The second mode is terrain-centric, where the user's viewpoint is fixed, and the cloud can be viewed moving across the terrain. Since the model was presented in a mobile AR application, typically viewed on a smartphone, providing different viewing perspectives was a challenge due to the relatively modest screen size. A simple, yet effective solution was implemented. While in the cloud-centric mode, the thunderstorm was locked to the image target and the terrain moved relative to the cloud. Under the terrain-centric mode, the terrain is locked to the image target, and the cloud moved.

Built-In Learning Activities for Aviation Training

In addition to the volumetric model, the application also provided two learning activities to assist with aviation training tasks: 1) take off under a microburst and 2) thunderstorm avoidance. The first activity simulates how a flight path during takeoff can be adversely, and dangerously, affected by a microburst. The model used airspeed, a flight take-off animation, and a representation of an intended and actual flight path to represent the potential damage while taking off under a microburst. The thunderstorm avoidance activity simulated a storm cell approaching an airport while a flight is planning for takeoff. This activity is designed with questions to ensure a trainee's understanding of the regulated operation under such conditions.

EVALUATION

Methods

Evaluation Objectives

The objective of the initial evaluation was to assess whether the thunderstorm model was effective in promoting learning. A future study with larger participants size will be performed for better understanding of the subject. The target audience for the model was students in aviation-related programs who were studying weather. The user evaluation assessed the impact of the interaction with a thunderstorm cell cycle model on students' knowledge and the usability of the activities.

Hypothesis

The user study evaluated whether completing weather-related educational tasks with an AR thunderstorm model helps students acquire knowledge about thunderstorms. The use of 3D learning objects in training can improve students' learning achievement in science, technology, engineering, and math (STEM) content areas (Estapa, 2015; Ibáñez & Delgado-Kloos, 2018). Therefore, students may improve their learning achievement in weather training through interaction with a 3D learning objects (thunderstorm model). Based on this, a hypothesis was developed that interaction with a 3D AR thunderstorm model will improve students' test scores in post-tests, as compared to pre-tests.

Participants

Students with some aviation weather knowledge were recruited for this study. A student with some weather knowledge was defined as anybody above the age of 18 who is enrolled in an aviation-related university program or a student who has recently begun private pilot ground school at a local airport or flight school, and who has been, or was currently enrolled, in a course related to aviation weather.

The participants included in the initial analysis were five male students with an average age of M = 19.8 (SD = 0.8) years. One had a commercial instrument rating, one had no ratings, one had a student pilot rating, and two had private instrument ratings. They had an average total flight hours of M = 74 (SD = 77.6). They had an average of M = 1.9 (SD = 2.6) instrument flight hours, and an average of 18.8 (SD = 25) flight hours in the last 60 days. Three had taken an aviation meteorology course, one had taken a Global Navigation and international planning course, and one had taken Private Pilot Ground School. They had an average M = 26.2 (SD = 41.9) hours of experience using AR/VR. All five used iPhones.

Tasks

The participant tasks were as follows:

1) Complete two pre-tests: one 10-question factual knowledge test and one 8-question visual knowledge test.
2) Thunderstorm cell lifecycle task: Read the text about the thunderstorm lifecycle, view the 3D AR thunderstorm model, and answer questions about the weather processes represented in the model.
3) Microburst Characteristics task: Read the text about microbursts, view the 3D AR microburst model, and answer questions about the weather processes represented in the model (Figure 9).
4) Complete the two learning activities:

    a. The effect of the microburst on an aircraft flightpath: Read the

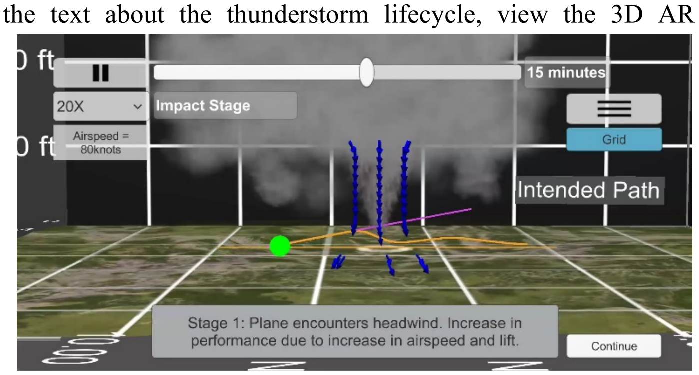

Figure 9. Microburst Characteristics.

text about the effect of the microbursts on an aircraft flightpath, view the 3D AR content about the effect of the microburst on an aircraft flightpath, and answer questions about the processes represented in the content.

b. Thunderstorm avoidance: Read the text about thunderstorm avoidance protocols, complete the AR activity about thunderstorm avoidance protocols, and apply the avoidance protocols to make decision in a takeoff situation.

5) Complete two post-tests: one 10-question factual knowledge test and one 8-question visual knowledge test, and the system usability scale.

The measures recorded in this study are provided in Table 1.

Table 1. Dependent variables and measures.

Dependent Variables	Metric	Data Type (Unit)	Method	Frequency
Factual knowledge	Textual quiz score	Percentage	Quiz	Pre/Post-trial
Visual knowledge	Graphical quiz score	Percentage	Quiz	Pre/Post-trial
System Usability	SUS	Scale 1-5	Questionnaire	Post-trial

Factual knowledge was measured using a 10-question textual quiz about thunderstorms with some questions from the Federal Aviation Administration's (FAA) commercial pilot written exam and some generated by the research team (Gleim & Gleim, 2020). For example, a student was given a written question about the updrafts in the developing stage of a thunderstorm lifecycle. They were asked to choose one of three statements that best characterized the speeds of the updrafts.

Visual knowledge was also measured pre- and post-trial using an 8-question graphical quiz about thunderstorms with questions about visible features that are adapted from questions on the FAA commercial pilot written exam and some generated by the research team (Gleim & Gleim, 2020). For example, a student was given an image of a microburst that contained a virga and dust ring. They were asked to choose one of the three statements that contained the names of the virga and dust ring.

System usability was measured post-trial with the System Usability Scale (SUS). The SUS is a common measure of perceived usability in human-computer interaction (Lewis, 2018; Lewis & Sauro, 2009; Sauro & Lewis, 2012a).

Study design and Procedure

The study was a within-subjects design, with results compared between the pre-tests and post-tests. Usability was assessed at the end of the experiment.

Prior to the study, students were given access to the AR thunderstorm application on their phone and asked to print the AR image target. Students met the moderator in an online video call, completed an informed consent form, and provided demographic information. Students completed pre-tests about their knowledge of thunderstorms. Next, students received instructions about the WeatherXplore application and completed a practice task where students used the application to interact with the cell life cycle animation and identify the stages. Students could explore the thunderstorm cell life cycle interface and ask the moderator questions if they chose to do so.

Students then began the four study tasks. Students first learned about the thunderstorm cell lifecycle. Students read the written materials, used the application to view the thunderstorm model, and answered questions related to the model. Students repeated this process three more times to learn about microburst characteristics, the effect of the microburst on a takeoff flight path, and avoidance protocols. After completing the four tasks, students completed the post-tests about their knowledge of thunderstorms and the system usability scale.

Data Analysis

Two-tailed paired-samples t-tests were conducted to compare the knowledge test scores in the pre-test and post-test conditions. The alpha level of .05 was used for all statistical tests. The effect sizes were calculated using Cohens D and categorized according to Cohen's thresholds where 0.3 is a small effect, 0.5 is a medium effect, and 0.8 is a large effect (Cohen, 1988).

Results and Discussion

Factual knowledge

Figure 10 illustrates the difference in factual knowledge quiz scores from the pre-test (M = 7.8, SD = 1.5) and post-test (M = 9.4, SD = 0.9). A two-tailed t-test was conducted to assess a significant increase in scores. The effect of interacting with the model on student test scores was not statistically significant, t(4) = -2.35, p = .07, d = 1.3.

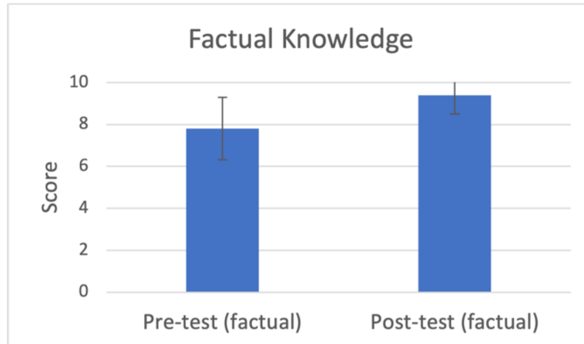

Figure 10. Factual knowledge pre-and post-test results.

Visual knowledge

Figure 11 illustrates the difference in visual knowledge quiz scores from the pre-test (M = 4.4, SD = 1.14) and post-test (M = 7.4, SD = .89) conditions. A two-tailed t-test was conducted to assess a significant increase in scores. The effect of interacting with the model on student test scores was significant, t(4) = -9.48, p = < .001, d = 2.92.

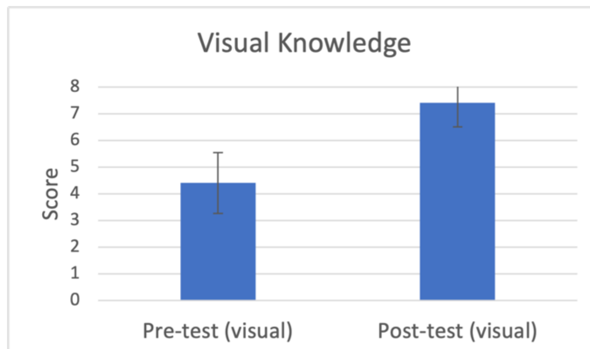

Figure 11. Visual knowledge pre-and post-test results.

Usability

Figure 12 shows the average system usability scale (SUS) score. The SUS was M = 77.5 (SD = 5.0) of 100 where higher scores indicate better usability. Using accepted industry standards for relative grading, scores of 68 are considered average and scores above 68 are generally positive scores (Sauro & Lewis, 2012b).

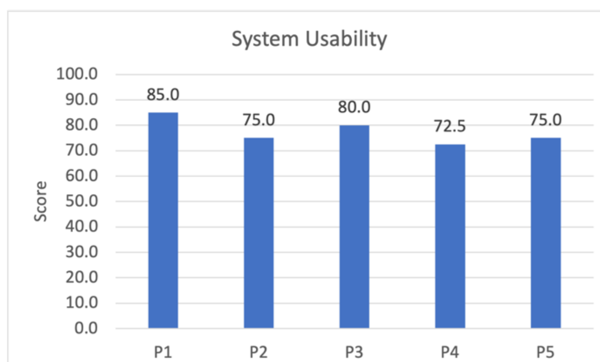

Figure 12. System usability scale scores.

Discussion

The initial results of the user study suggest that the learning activities had an impact on student knowledge, and students perceived them as usable. The initial results of the factual knowledge tests were not significant. However, these initial results only include 5 participants, and testing with more participants may generate significant results. The results of the visual knowledge tests were significant. The results suggest that the AR training tasks influenced students' visual knowledge. Specifically, the results suggest that when students use the AR content their visual knowledge increases. Finally, the usability scores in this study suggest that the AR training tasks were perceived as usable by the students. The initial results are promising, and future work will be to conduct a full study.

CONCLUSION

According to reports, over 25% of GA accidents are related to weather. In those accidents, general turbulence and thunderstorm were the top fatal factors (Fultz & Ashley, 2016). Traditional GA training on thunderstorms is delivered mainly by images, text or video, which does not provide an immersive and effective training environment. In the military, current high-fidelity simulators may not be easily accessible to students in their initial flight training and will increase the training cost. In addition, classroom instruction is limited in effectiveness of teaching weather hazards. The AR application developed by the researchers provides a detailed representation of thunderstorms using a volumetric thunderstorm model. The model provides various approaches to deliver weather information to overcome the limitations of traditional training methods. On the initial evaluation of the model, the results show significant improved outcomes while using the model for thunderstorm learning. This tool can also be implemented in civilian and military aviation training, especially at the private pilot stage to enhance pilots severe weather event response. This model can be used as an assisting tool with other learning material to enhance student pilots' understanding of the hazards associated with thunderstorms and how to recognize and avoid them.

In the future, 3D learning objects such as the thunderstorm model will be integrated into different scenarios to enhance pilot learning outcomes. More variations on the model will also be developed to simulate different types of thunderstorms and other weather phenomenon which pilots might encounter during flight.

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