Research Article

Designing Three-Dimensional Augmented Reality Weather Visualizations to Enhance General Aviation Weather Education

—Philippe Meister, Jack Miller, Kexin Wang, Michael C. Dorneich, Senior Member, IEEE, Eliot Winer, Lori J. Brown, and Geoffrey Whitehurst

***Abstract*—Objective**: *We designed, developed, and evaluated a 3D augmented reality (AR) weather visualization to investigate whether it could enhance communication about weather in general aviation (GA) education.* **Background**: *Evaluations of GA weather training identified gaps in training where students lack the ability to correlate weather knowledge to inflight decision making.* **Literature review**: *3D AR learning objects have been used in the sciences to make representations of multidimensional natural phenomena more accessible in classroom settings, and they offer the promise of enhancing communication about weather.* **Research question**: *Can smartphone- and tablet-based 3D AR weather visualizations be effective tools to enhance current GA weather education?* **Methods**: *A 3D AR thunderstorm cell lifecycle visualization was designed and developed. A preliminary evaluation of the application for GA weather training was conducted with one certified flight instructor, one university aviation meteorology instructor, one university thunderstorm expert, and three students to assess whether the AR thunderstorm visualization can communicate weather theory and whether the interfaces are usable for learning and task completion.* **Results**: *Students' knowledge of thunderstorms increased after using the visualization to explore the dynamics of the thunderstorm lifecycle and various aspects of thunderstorms. Experts felt that the learning experience met their expectations of what they wanted to communicate about thunderstorm theory. The AR interfaces were rated as usable for learning interactions and produced low levels of workload.* **Conclusion**: *The communication of thunderstorm theory was supported by the animation and interactivity of the visualization, and has the potential to enhance current general aviation weather education.*

Index Terms*—Augmented reality (AR), aviation decision-making, thunderstorms, visualization, weather.*

Augmented reality (AR) and virtual reality (VR) applications are designed and developed for several industries including the military, gaming, and education [1], [2]. The design of these applications for technical communication has been investigated in terms of the development teams, interfaces, tasks, and human factors [1], [3]–[6]. General aviation (GA) weather education is one area where new AR applications may be used to deliver educational content, overlayed onto the traditional curriculum, to create interactive print educational materials. These applications may be used to enhance communication about the dynamics of aviation weather with students in the classroom and help bridge the gap between paper-based weather education and in-flight experiences or decision making [7], [8]. This article describes a preliminary evaluation in which we designed, developed, and evaluated a 3D AR thunderstorm visualization to test whether it could be an effective tool to enhance GA weather education. This preliminary evaluation provides early evidence that the 3D AR thunderstorm visualization may enhance the communication of weather theory and may be effective for enhancing student pilot weather education.

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Practitioner Takeaway

- Augmented Reality (AR) 3D visualizations of weather have the potential to enhance aviation weather education.
- Students' knowledge increased as they were able to layer, animate, and explore 3D thunderstorm models.
- Implementation of AR weather visualizations on smartphones broadens the accessibility of weather education resources for pilots.

Motivation Weather-related accidents are a continuing safety threat and a monetary cost to GA in the US [9]–[12]. These accidents occurred between 36 and 65 times annually from 2006 to 2015, and fatalities occurred between 28 and 47 times annually during the same period [10]. These accidents have estimated costs between $1.64 billion and $4.64 billion [13]. Inexperienced student GA pilots generally lack weather experience, which can be a strong predictor of their ability to make safe weather-related decisions and which can contribute to inadvertent weather-related accidents [12]. As pilots become more experienced, they learn about weather and develop effective strategies to find weather information [14], recognize weather cues [15], assess weather situations [16], judge visibility [17], and perceive weather-related risks [18].

Problem Certified flight instructors (CFIs) and student pilots communicate about weather as a part of flight training. Training curricula have shown gaps in how students learn to correlate weather knowledge with weather-related situations, particularly when it comes to making decisions about flying from visual meteorological conditions (VMC) into instrumental meteorological conditions (IMC) [19]. Identified gaps include the following:

1. Lack of opportunity for student pilots to experience different weather patterns and associated visual cues
2. Perceived lack of skills related to changing from VMC to IMC decision-making
3. Lack of situational awareness related to changing from VMC to IMC
4. Lack of retention of weather knowledge
5. Lack of ability to correlate, interpret, and apply weather information related to changing from VMC to IMC weather factors [19]

Furthermore, a national survey of GA pilots reported that just under 16% of GA pilots felt that their education and training prepared them "poorly" or "very poorly" to deal with "real life" weather events [12]. Current weather education can be improved to help students develop more robust weather knowledge and apply it more effectively in weather-related aviation situations.

Challenge The lack of accessible, sophisticated, realistic representations of weather may hinder communication about weather between CFIs and students in classroom settings. Weather phenomena are 3D, with spatial and temporal dynamics that are particularly difficult to communicate to students using static 2D representations in the classroom. Traditional printed training materials provide static 2D representations of weather that may constrain communication about the dynamics of weather, such as the thunderstorm cell cycle. Although flight simulation and advanced training devices can provide sophisticated, realistic 3D representations of weather, they can be expensive and not always readily accessible to the entire GA community [20]. When student pilots are trained in VMCs in an aircraft, they do not have the opportunity to thoroughly explore aspects of dangerous weather hazards in-flight such as thunderstorm hazards [12].

Potential Benefits Increased access to 3D weather visualizations may enhance communication about the weather in classroom settings. 3D, interactive, and animated visualizations have been used in the sciences to make hard-to-see natural phenomena, such as magnetism and electromagnetism [21], [22], more accessible in the classroom [2]. These AR learning objects help students improve their motivation to learn [23], develop more robust conceptual knowledge [24], and better remember spatial information [25]. Interactivity and animation may further support the acquisition of knowledge and the development of mental models, as has been done with interactive videos [26]. AR weather visualizations that are 3D, interactive, and animated may have similar impacts on student learning in GA weather education [27]. These impacts may engage and better prepare student

pilots for subsequent ground school training and flight.

Approach We aimed to test whether AR visualization could enhance communication about the weather in classroom settings by designing and developing 3D AR weather (thunderstorm) visualizations and integrating them into text-based learning materials [25]. This process is similar to how a quick response (QR) code works, using actual images in the text that relate to the content. This method is called "interactive print." The documents are created by placing AR targets within the document at specific locations. Students scan the AR target with an AR smartphone application and see the digital 3D learning object on their smartphone screens. The AR learning object is digitally placed in the document at specific points to provide context-appropriate spatial information in the learning environment [28]. Effective interactive print is designed to immerse the user, provide instant feedback, and help the student focus on high-level cognitive tasks that require engagement with the digital content [29]. Thus, a critical first step taken in this article is to design weather visualizations that immerse, motivate, and engage students in learning tasks.

Research Question

This study investigated the following research question.

> **RQ.** Can smartphone- and tablet-based 3D AR weather visualizations enhance GA weather education?

To investigate the question, we designed, developed, and implemented a 3D visualization of a single-cell thunderstorm cell lifecycle and tested it with one CFI, one university aviation meteorology instructor, one university thunderstorm expert, and three students. The preliminary evaluation had the following two goals:

1. Assess the effectiveness of the AR thunderstorm visualization to communicate weather theory
2. Assess the usability of the interface for learning and task completion

Literature Review

The following sections review related work to describe the potential for using 3D AR weather visualizations to enhance the representation of weather theory in GA weather education. Previous work in GA weather education is described to identify the current gaps that may be addressed with 3D AR visualizations. Previous efforts to visualize 3D information are described to explain how people enhance the transfer of visual information to users. The literature about AR is described to articulate the value of these immersive AR applications for GA weather education.

Representing Weather in GA Education

Instructors communicate with students about weather in GA education. Weather is a complex topic because it is the most dynamic and least predictable variable in the National Airspace System [30]. Weather phenomena vary in their spatial characteristics, development over time, and intensity. Representations of aviation weather can include the types of weather-related accidents that occur most frequently. For example, in 2015, the leading causes of weather-related accidents were transitioning from VMC to IMC (21 occurrences), thunderstorms (5), icing (5), poor IFR technique (4), and turbulence (3) [10]. Pilots' responses to weather can include important aspects of cognition in weather-related situations, including decision-making [31], [32]; cue recognition [33], [34]; situation awareness [35]; and experience [36].

Although weather communication occurs throughout training, weather may still be an underrepresented area of training, with gaps in training outcomes [19], [37]. Research into weather communication can help develop new ways of helping students learn to correlate weather knowledge with weather-related situations and make effective weather-related decisions [19]. The work in this article, to design and develop 3D AR weather visualizations, may address these gaps in training by helping students integrate knowledge about various aspects of thunderstorms and correlate their knowledge more effectively in weather-related aviation situations.

Communicating Through 3D Visual Information Design

Visual information design can enhance the communication of visual information [38]. Visualizations serve specific communicative purposes for target audiences, such as presenting images, representing quantities, or sequencing a narrative [39]. In scientific and technical communities, these visualizations can be developed with the visual techniques of maps and statistical graphics to improve precision and quantification [39]. 3D visualizations are becoming more prevalent because there are additional ways to deliver them to users, including Web GL, 3D PDF, AR, and VR.

3D visualizations have been used to enhance visual and verbal communication in various domains. These visualizations represent the spatial and temporal dimensions of large multidimensional objects and are effective educational tools. Authors benefit from the ability to synthesize information into one complete 3D visualization rather than fragment information into multiple 2-D visualizations. For example, in a study of anatomy, multiple 2-D images of an anatomical system were compiled into a more complete 3D representation, improving the description of the form-function relationships [40]. Viewers also benefit from the ability to view and interact with the composite visualization. In a study of astronomy, 3D visualizations allowed viewers to

> actively rotate, zoom, and pan multidimensional datasets to find a viewpoint that provides more information and understanding. [41, p. 600]

3D weather visualizations may provide similar benefits, allowing the development of a more complete representation and allowing students to view it for better understanding.

In addition to enhancing visual communication, 3D visualizations can substitute for linguistic explanations of weather. Speakers may refer to the visual representation instead of translating visual information into verbal language. Similarly, listeners may view the representation instead of translating verbal language into a mental image. For example, medical staff used 3D artwork to make medical jargon more understandable to patients, thereby improving their understanding and reducing their anxiety about procedures [42]. 3D weather visualizations may enhance communication similarly by supplying a visual representation of linguistic information and helping CFIs and students communicate weather theory, weather dynamics, and weather jargon.

Augmented Reality 3D visualizations can be delivered using AR technologies in aviation weather education. AR refers to semi-immersive virtual environments that provide additional computer-generated perceptual information overlaid onto a real-world scene [43]. AR is used in aviation training for flight procedure training, cabin crew training, and maintenance training [44]–[46]. Military pilots use AR-enhanced views to navigate and perform combat tasks [43]. These AR systems help users complete tasks and develop mental models [26], [47]. The development of robust mental models is an asset in aviation training because they are an important component of good weather-related decision-making in the cockpit [48], [49].

In classrooms, AR has been used to enhance traditional text-based learning and has produced benefits in learning and motivation [2], [25]. Complementary AR learning experiences benefit reading comprehension and understanding spatial data [25]. In a study of AR-enhanced learning about electromagnetism, the AR-enhanced learning group scored 12% better on the post-test than the control (print learning) group. The AR-enhanced learning group then scored significantly better than the print learning group on a follow-up retention test, with average scores of 55% for the AR-enhanced group and 45% for the print group [25].

Systematic reviews of academic publications about AR in education summarize the implementation techniques and educational outcomes [2], [50]. In a review of 68 publications published between 2007 and 2015, AR was often (60%) delivered using mobile devices because they are cost-effective and familiar to users [50]. In these publications, AR was often (59%) generated above a marker placed in the real world. The marker assumes a context when placed on specific objects or in specific documents. In a different review of 32 academic publications published between 2003 and 2013, AR was most often (46%) used in the sciences where instructors create visualizations to make natural phenomena more accessible in the classroom [2]. Some 44% of these studies reported learning gains, and 31% reported benefits to students' motivation [2]. These studies suggest that smartphone-based AR can make weather phenomena more accessible in the classroom and may impact student motivation and learning.

Thunderstorm Visualization Design

We designed and developed an AR visualization of the lifecycle of a single-cell thunderstorm. The thunderstorm cell lifecycle is a part of the ground training related to the Federal Aviation Administration (FAA) Airman Certification Standards (ACS) in the private pilot practical and written examinations (knowledge codes PA, I, C, K3h) related to the weather information tasks in the thunderstorms and microbursts category [51] and the airman knowledge private pilot testing statements code PLT495 [52]. Thunderstorm cell lifecycle theory is a part of the weather hazards module required in FAA ground training for the private, instrument, and commercial pilot certifications [51].

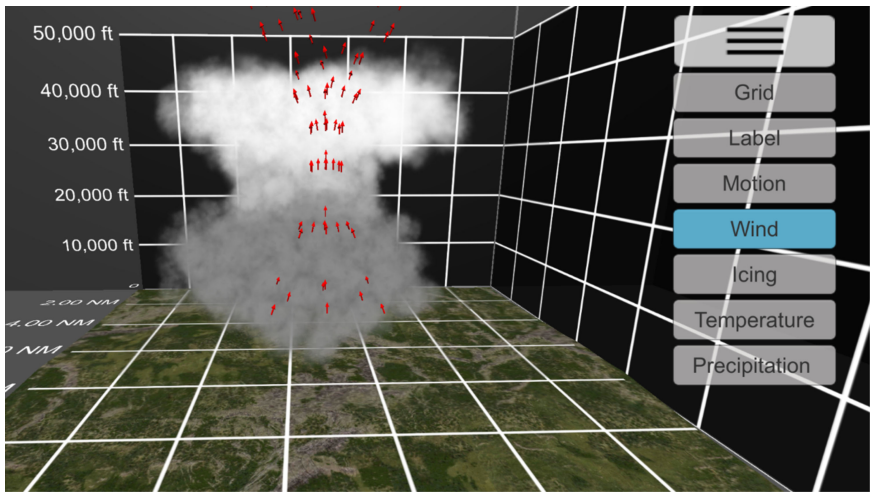

Fig. 1. Thunderstorm cell lifecycle visualization with the distance grid and wind arrows.

The thunderstorm cell lifecycle visualization was informed by the FAA Advisory Circulars (AC) AC No. 00-6B and AC No. 00-24C [53], [54]. The researchers developed the thunderstorm cell lifecycle visualization using Unity 3D and implemented it as an AR application in the WeatherXplore application for Android and iOS smartphones and tablets that connects digital weather content with aviation educational material [55]. The AR application registers an AR image target and generates the visualization based on the position of an image target. A particle system was used to develop the volumetric visualization and make the thunderstorm clouds and precipitation visually realistic. Users can control the visualization with the user interface on the device screen space.

The visualization incorporated interactivity to allow students to layer various aspects of the thunderstorm cell lifecycle. Interactivity has been shown to support learning in previous training applications, and therefore was expected to help make the visualization an effective tool [25], [27], [56]. Layering parts of the whole has also been an effective strategy for information design [38]. The lifecycle visualization depicts a grid, labels, motion, wind, icing, temperature, and precipitation (see Fig. 1). The user interface provides buttons to toggle these features on and off.

Thunderstorm Cell Lifecycle Stages A thunderstorm cell is the convective cell of a cumulonimbus cloud having lightning, thunder, and three distinct stages [53]. Students develop knowledge of the stages to better understand evolving weather phenomena and the hazards present in each stage. The stages are shown with cloud movement and wind arrows (see Fig. 2). A strong convective updraft with speed up to 3000 ft/min and vertical cloud growth characterizes the developing stage. Both updrafts and downdrafts and the development of an anvil cloud blown horizontally by winds aloft characterize the mature stage. A strong downdraft with speeds up to 6000 ft/min and cloud dissipation from the ground up characterize the dissipating stage.

Grid The grid is a network of lines that depict vertical altitude (feet) and horizontal distance (nautical miles). This grid in this visualization provides a measurement for 12 nautical miles in the horizontal direction and 50,000 ft in the vertical direction. The instructional goal is to help students understand the size of the cell and related weather processes.

Labels The labels provide text to accompany the visualization and provide supplemental information (e.g., wind speeds). The instructional goal is to augment graphical information with specific numerical information to enhance student understanding of significant quantitative values such as high wind speeds. For example, when winds are displayed, labels identify the fast updrafts (3000 ft/min) and downdrafts (6000 ft/min).

Motion The user has multiple ways in the app to display the advective movement of the thunderstorm relative to the ground. In the stationary view, the thunderstorm is centered on the screen and the ground moves under it. Alternatively, toggling the motion button will

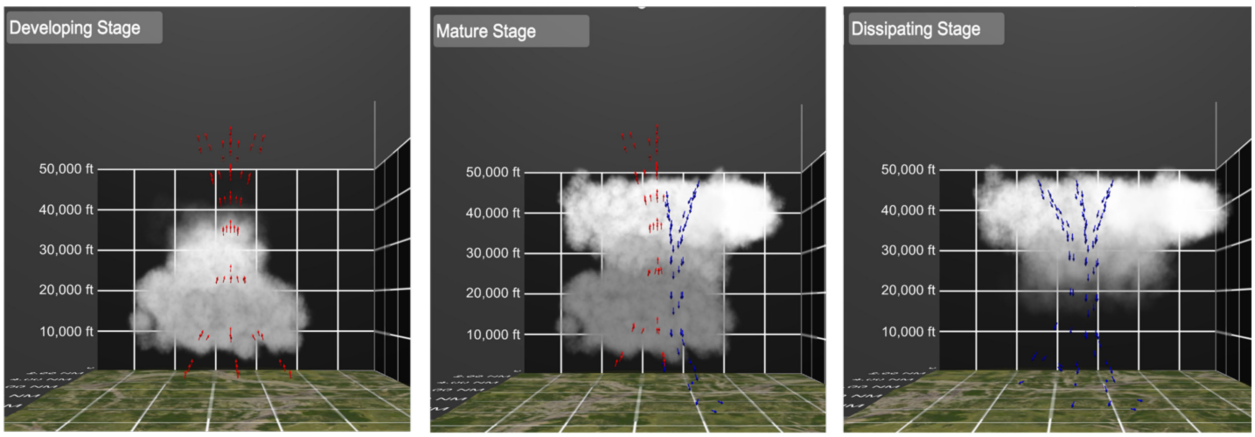

Fig. 2. Thunderstorm lifecycle stages: developing (left), mature (center), and dissipating (right).

change the view so that the thunderstorm cell moves across the stationary ground. The instructional goal is to allow users to focus on the thunderstorm or its lateral motion while clarifying that the thunderstorm cell is not stationary.

Wind Wind depicts the movement of air through the cloud as a series of moving arrows. The instructional goal is to convey how the wind patterns change as the thunderstorm matures through the three stages of the cell lifecycle. The developing stage has a strong updraft. The mature stage has an updraft and a downdraft. The dissipating stage has a strong downdraft. These winds can create severe turbulence.

Icing Icing is caused by atmospheric conditions that can lead to the formation of water ice on an aircraft. The instructional goal is to show the altitudes likely to have severe icing hazards. Temperatures below freezing (between 0°C and −15°C) may have supercooled liquid droplets and cause the most severe icing [57]. Standard icing symbols presented in the areas of the visualization where icing is likely to occur are based on precipitation and temperature.

Temperature Air temperature is a measure of the average kinetic energy of the particles in the air. The instructional goal is to show the range of temperatures and the point where freezing temperatures occur. The temperature in this visualization is 20°C at sea level, decreases by 2° per 1000 ft, and is −60°C at 40,000 ft altitude. The user interface provides a button that toggles a color gradient on and off. The color gradient has a color key that students use to read the temperature at various altitudes in the thunderstorm.

Precipitation Precipitation refers to any water particles that form in the atmosphere and fall to the ground. The instructional goal is to show the positions where rain and hail occur. Hail is formed when rain is blown upward by an updraft into freezing temperatures. Hail can be blown by winds aloft up to 20 miles away from the core of the thunderstorm under the anvil.

Methods

A preliminary evaluation was conducted with the following two goals:

1. Assess the effectiveness of the AR thunderstorm visualization to communicate weather theory
2. Assess the usability of the interfaces for learning and task completion

The Institutional Review Board (IRB) approved the study. The CFI and expert reviews were conducted to assess the accuracy and effectiveness of the visualization for training. The expert review provides meaningful qualitative validation if a

> specified set of explicitly qualified subject matter experts reviewing a [model or simulation] conclude that specified characteristics show expected responses for specified portions of the [application domain]. [58, p. 12]

An AR usability study supports effective educational material design [59] and was conducted to assess the usability of the visualization with instructors and students.

Participants The six participants for this preliminary evaluation included one CFI, one university aviation meteorology instructor, one

university thunderstorm expert, and three students. Two of the experts provided input into the original AR and study design, and one expert had no input before the evaluation.

The CFI has more than 30 years' experience as a professor of aviation and possesses an Airline Transport Pilot rating, as well as instrument ground instructor and advanced ground instructor ratings, with more than 30 years of aviation experience and 6500 flight hours. She has 200 hours of experience working with AR/VR technologies.

The university aviation meteorology instructor has more than 20 years of experience teaching aviation students about meteorology and other aviation subjects. He holds a private pilot certificate with 200 flight hours and previously flew for 20+ years in the UK Royal Air Force as a navigator. He has 50 hours of experience advising on working with AR/VR technologies.

The university thunderstorm expert has 25 years of experience teaching and researching synoptic and mesoscale meteorology emphasizing weather forecasting, especially thunderstorm evolution. He is very knowledgeable about issues relating to aviation and has experience verifying forecasts. He has 100 hours of experience advising on working with AR/VR technologies and served as a meteorology expert on a previous effort to model a tornadic thunderstorm in VR.

The three engineering student participants represent an appropriate proxy user group to inexperienced aviation students or student pilots who would not have much exposure to weather instruction early in their training. In this study, these students were trained in basic thunderstorm knowledge, not aviation, and therefore aviation students were not necessary for this study. They were engineering graduate students all 25 years of age. None were pilots, and none had more than general knowledge of aviation weather. One had 10 hours of experience with AR/VR technologies, whereas the other two had 1 hour or less.

Procedure The participants began the evaluations with a briefing and informed consent. The students first took a knowledge pretest about the thunderstorm cell lifecycle. The experts were asked to describe their expectations for an instructional thunderstorm visualization. Then, all participants were trained on how to use the WeatherXplore application and the 3D visualization.

TABLE I
PARTICIPANTS AND TASKS

Task Type	Who?	Task
Expectations	Experts	Describe expectations.
Pre-test	Students	Answer six questions about thunderstorms.
Task 1	Both	At which stage of the life cycle do both up- and down-drafts occur?
Task 2	Both	What is the speed of a typical updraft in the developing stage?
Task 3	Both	At which stage of the lifecycle does rain fall to the surface of the earth?
Task 4	Both	How fast and far does the cell move across the ground?
Task 5	Both	At what altitude is the potential for icing in this model severe?
Task 6	Students	At what temperatures is the potential for icing severe?
Review	Experts	Review the model.
Post-test	Students	Answer six questions about thunderstorms.
Comments	Both	Provide open-ended written comments.

All participants completed a series of five tasks with the visualization. The three students also completed an additional sixth task. In each task, participants were prompted with a question (see Table I) and then navigated the screens to find the appropriate answer. Following each task, they completed the NASA TLX workload scale to provide subjective data regarding whether the AR task was cognitively demanding and a questionnaire to provide subjective data about their perceptions of the AR content while completing the task. The TLX has six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration.

After completing all study tasks, they completed the system usability scale (SUS) to provide subjective data about whether the tool was usable for training, explored and reviewed the visualization in an unmoderated session, and provided open-ended comments to offer their qualitative opinions and feedback about the tool. Finally, the students completed a knowledge post-test about the thunderstorm cell lifecycle. Table I summarizes the procedure.

Data Collection and Analysis The preliminary evaluation generated quantitative data and qualitative statements. The quantitative data were summarized with descriptive statistics. Given the small sample size, the scale-based measures from 1 = Strongly disagree to 5 = Strongly Agree were described with median and interquartile range (IQR) when $N > 3$ and were reported individually when $N = 3$. The SUS scores, calculated using an established scoring procedure that resulted in a score out of 100 points, were described with median and IQR. The results for the knowledge pretests and post-tests were each averaged.

TABLE II
DATA COLLECTION

Type	Data Collection	Type/Units	Method	Time
Expert expectations	Thunderstorm content	Written statements	Written	Pre-trial
	Visualization	Written statements	Written	Pre-trail
	Learning with the visualization	Written statements	Written	Pre-trail
	Interaction with the visualization	Written statements	Written	Pre-trail
Expert review	Visualization	Scale 1-5 (Disagree/Agree)	Survey	Post-trail
	Visualization information	Scale 1-5 (Disagree/Agree)	Survey	Post-trail
	Visualization representation	Scale 1-5 (Disagree/Agree)	Survey	Post-trail
Training	Expected effectiveness	Scale 1-5 (Disagree/Agree)	Survey	Post-trial
	Qualitative statements	Written statements	Written	Post-trail
Knowledge	Student knowledge	Number	Survey	Pre/Post
Devices	Device appropriateness	Scale 1-5 (Disagree/Agree)	Survey	Post-trial
	Qualitative statements	Written statements	Written	Post-trial
Task completion	Time on task	Seconds	Timer	Post-task
	Task completion correctness	Percentage	Survey	Post-task
	Task completion confidence	Scale 1-5 (Disagree/Agree)	Survey	Post-task
	Qualitative statements	Written statements	Written	Post-task
User interface	Workload (TLX)	Scale 0-21	Survey	Post-task
	System Usability Scale	Scale 1-5 (Disagree/Agree)	Survey	Post-trial
	Qualitative statements	Written statements	Written	Post-trial

The qualitative written statements were cataloged in a spreadsheet and organized by prompt and participant. The participants' response statements were analyzed using a pragmatic iterative approach [60]. Primary coding identified the topics in the statements. After a topic was identified, additional information related to the topic was gathered from the remainder of the statement. Topics were recorded and analyzed for frequency. Themes were developed when appropriate by combining relevant topics (e.g., types of weather hazards). Table II summarizes the data collection.

Testing Environment Four participants (one university thunderstorm expert and three students) completed the study in a university usability lab. The CFI and university aviation meteorology instructor participated at a distance and conducted the study in their chosen workspace. The usability lab had two rooms separated by a window. The room for the participants was about 25 ft by 20 ft and contained a worktable and a computer table with a desktop computer. The room did not have any bright exterior windows. Participants used an iPhone XR with WeatherXplore and the AR image target on the worktable to complete study tasks. Participants used the computer to complete the digital study booklet. The audio capability between the rooms allowed the moderator to provide instruction and the participant to ask the moderator questions.

RESULTS

Expectations The numbers in parentheses in this section indicate the number of responses containing the indicated topics.

Expectations for Thunderstorm Content: The experts expected the thunderstorm content to include thunderstorm phenomena, theory, and avoidance. Thunderstorm phenomena included winds (3), clouds (3), turbulence (3), precipitation (3), hail (3), temperature (2), movement (2), updrafts (2), downdrafts (2), icing (2), lightning (2), microburst (1), windshear (1), and graupel (1). Thunderstorm theory included the stages of the cell lifecycle (2). Thunderstorm avoidance (1) included the recognition of weather hazards (1) and specifically deteriorating visibility (1).

Expectations for the Visualization: The experts expected the visualization to depict hazards (3), lifecycle stages (2), dynamic weather changes (1), lightning (1), and graupel or hail (1). They also expected it to depict low visibility in thick clouds (1), precipitation (1), and the ways that different hazards affect pilot decision-making (1).

Expectations for Enhancements to Learning: The experts expected the thunderstorm visualization to help students better "visualize," "appreciate," and "understand" weather factors. They specifically

expected it to enhance students' learning about thunderstorm hazards (2), cell lifecycle stages (2), the effects of thunderstorms on aircraft (1), intense thunderstorm motions (1), turbulence (1), precipitation (1), and lack of visibility (1).

Expectations for Student Interactions With the Visualization: The experts expected beneficial student interactions to include selecting different aspects of the weather phenomena (2), changing how they are flying to avoid conditions including updrafts and downdrafts, low visibility, and intense lightning (2), and seeing how wind shifts affect aircraft performance (1).

Review

Review of Visualization After using the visualization, the experts agreed that the visualization matched their expectations for an educational thunderstorm visualization (scores = 5, 4, 4 on a scale of 1–5). The university thunderstorm expert described the visualization as "a very good 3D version of the classic schematic shown in introductory meteorology textbooks."

In addition to the current visualization, the CFI said that she "would like to see how this affects aircraft."

Review of Visualization Information The experts agreed that the visualization includes the required information about a single-cell thunderstorm (scores = 4, 4, 4 on a scale of 1–5). The university thunderstorm expert said, "For the simple 3-stage cell model, this 3D model does include the necessary information to understand the storm."

However, the CFI and university aviation meteorology instructor suggested that in the future, phenomena such as turbulence, hail, wind shear, and microbursts could be added to the visualization.

Review of Visualization Representation The CFI and the university aviation meteorology instructor felt that the representation was accurate, but the university thunderstorm expert did not (scores = 4, 4, 2 on a scale of 1–5). The university aviation meteorology instructor stated that it "gives a good 3D view of the developing storm." The university thunderstorm expert said that "this would be a good first step for aviation weather training" but noted that "this type of thunderstorm only represents one small piece of what happens in nature." He suggested including "organized thunderstorm systems such as squall lines, where pilots often have to navigate through narrow holes" and a variety of wind speeds in the updrafts and downdrafts, in addition to the peak value.

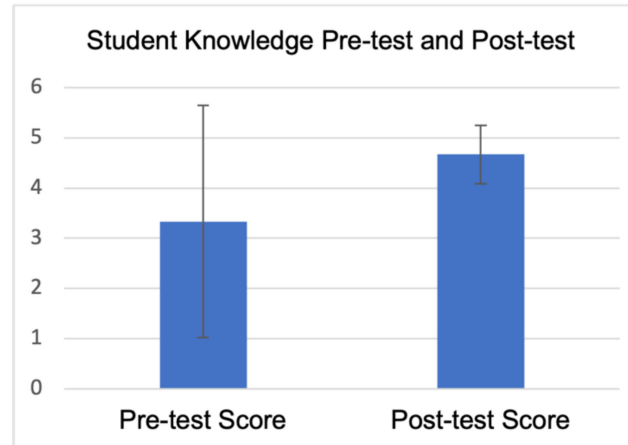

Fig. 3. Student knowledge pretest and post-trial test scores.

Training The experts agreed that the application would be effective to enhance GA weather education (scores = 5, 4, 4 on a scale of 1–5). The university aviation meteorology instructor stated that

> This is a great tool for any instructor as it provides a very good 3D representation of the development of the thunderstorm and how different factors in the storm generate the different hazards that are discussed when learning about thunderstorms.

The university thunderstorm expert stated that the visualization helps "cover the most basic understanding of thunderstorms." However, the experts suggested that additional content would make the visualization more effective, including hazards to a flight, the effect of thunderstorms on a flight, thunderstorm avoidance, and multicell storms.

Knowledge The average student pretest score was $M = 3.3$ (SD = 2.3) of 6 and the average post-test score was $M = 4.6$ (SD = 0.57) of 6 (see Fig. 3).

Task Completion Table III summarizes the results for correctness, confidence, and time. Participants completed the first three tasks with a relatively high level of correctness. They completed

TABLE III
TASK COMPLETION TIME, CORRECTNESS, AND CONFIDENCE

Tasks	Median (IQR*) Correctness in Percent	Median (IQR*) Confidence on 1-5 Scale	Median (IQR*) Time in Seconds
1. Winds	100% (0)	5.0 (0.8)	50.0 (42.5)
2. Updraft speed	85% (0)	3.0 (2.3)	50.0 (24.3)
3. Precipitation	100% (0)	3.0 (1.5)	37.5 (26.8)
4. Cell movement	50% (100)	3.0 (1.5)	31.0 (14.0)
5. Icing altitudes	50% (75)	3.5 (1.0)	50.0 (23.5)
6. Icing temperatures	0% (0)	4.0 (0.0)	59.0 (17.0)

∗*Note:* IQR is the difference between the 75th and 25th percentiles of the dataset.

tasks 4, 5, and 6 with a lower level of correctness. The experts reported issues completing task 4 (cell movement) because the grid was large, and the grid labels were difficult to see. The experts reported issues completing task 5 (icing altitudes) because the distance between the thunderstorm cell and the grid created issues for estimating the height. The three students reported issues completing task 6 (icing temperatures) because the colors of the icing symbol (icing) against the colors of the cloud (temperature) made reading difficult.

Devices The experts strongly agreed that the devices are appropriate for GA weather education (scores = 5, 5, 5 on a scale of 1–5). The university aviation meteorology instructor stated that "everyone has, or has access to, either a smartphone and or tablet."

USER INTERFACE

Workload The NASA TLX workload subscale scores had Mdn = 4.0 of 20 (IQR = 7.0), where lower scores indicate lower workload [61]. The workload was measured immediately after the user completed each study task. Mental demand had the highest median subscale score of Mdn = 7, and the remaining subscales (physical demand, temporal demand, performance, effort, and frustration) were relatively similar with medians between 1 and 4. Table IV summarizes the results of workload for each task.

SUS The SUS scores had Mdn = 75 of 100 (IQR = 9.4), where higher scores indicate better usability. Scores ranged between 62.5 and 80. Scores above 68 are considered positive using generally accepted industry standards [62].

Qualitative Statements About the Interface The CFI, professors, and students described the user interface elements as conveniently placed and easy to use. The experts liked that the thunderstorm content immediately changed after manipulating the controls. The CFI and university aviation meteorology instructor suggested that users should be able to select icing and temperature simultaneously because they are linked to one another. Students described the navigation as easy to use.

TABLE IV
TASK WORKLOAD SCORES

Tasks	Median (IQR*) of Raw Average Workload on 1-20 scale
1. Winds	2.0 (3.0)
2. Updraft speed	2.0 (5.5)
3. Precipitation	1.5 (3.0)
4. Cell movement	7.0 (8.0)
5. Icing altitudes	5.5 (6.0)
6. Icing temperatures	5.5 (10.8)

∗*Note:* IQR is the difference between the 75th and 25th percentiles of the dataset.

DISCUSSION

Our preliminary evaluation had the following two goals:

1. Assess the effectiveness of the AR thunderstorm visualization to communicate weather theory
2. Assess the usability of the interfaces for learning and task completion

The evaluation also generated information on the appropriateness of smartphones for training and future work.

Effectiveness of the Visualization in Representing Thunderstorm Theory The results of this preliminary evaluation indicate that smartphone-based 3D AR thunderstorm

visualization could be an effective tool for enhancing weather education related to thunderstorms. The experts rated the effectiveness of the training highly. They commented that the tool provided a good 3D representation of thunderstorm development and thunderstorm hazard formation, and that the tool met their expectations of the phenomena covered in 3D thunderstorm training. The students completed all the learning tasks with reasonable workload levels and improved their knowledge by interacting with the visualization.

Animation of thunderstorm dynamics helped communicate the dynamic aspects of thunderstorm theory. Animation has supported learning in previous training applications and therefore was expected to help make the visualization an effective tool [26], [27]. The experts made comments to confirm that animation is expected to support communication. The university aviation meteorology instructor said, "It provides a very good 3D representation of the **development** of a thunderstorm." The university thunderstorm expert said,

> I believe it is not possible to fully understand the **intense motions** and turbulence in a thunderstorm without being exposed to it in a rather realistic fashion, such as might be possible in a 3D interactive model.

Further study could test whether the animated visualizations are more effective than a static schematic or video representations in aviation training.

Interactivity with different visualization layers helped communicate various aspects of thunderstorm theory. Students used the interface in this study to select individual visualization layers to toggle on and off, including wind, precipitation, temperatures, and icing. Students viewed each of these layers individually to complete tasks but were less successful in completing Task 6 that explicitly asked them to view multiple layers together. Future work can investigate the design of layers that work well together to represent meaningful relationships and study the grouping of these layers to support task completion.

Students learned about thunderstorms through interacting with the visualization. The student knowledge test score average improved from the pretest to the post-test. Students successfully completed chunked learning interactions to identify the cell lifecycle stages, wind patterns, wind speeds, precipitation timing, movement distances, and temperatures. Chunking interactions into learnable amounts of information improves how users learn about concepts and processes [61]–[64]. For example, in this study, information was chunked to help students learn about the winds throughout the cell lifecycle. In addition to chunking, future studies can investigate the scaffolding of learning interactions by cognitive function to support learning [65].

The Usability of the Interfaces for Task Completion The interfaces were rated as usable for task completion and did not produce high levels of workload. The interfaces for the thunderstorm visualization, visual layers, and animations were used effectively to complete Tasks 1-3. However, all participants completed Tasks 4 and 5 less correctly than the first three tasks.

In Task 4, users had difficulty assessing cell movement against the grid because the grid labels were difficult to see. The grid may not show cell movement clearly because the user must track the cell movement from beginning to end and then use the gridlines to estimate the distance. An alternative method would be to trace the cell movement across the ground and label the exact distance it has moved.

In Task 5, users had trouble estimating the altitude with possible severe icing because the grid was difficult to use for height estimation. The university aviation meteorology instructor suggested adding dashed lines through the cloud to help users assess height. This alternative would help users align the thunderstorm cell with the gridlines behind it to better estimate altitude. The usability of the grid should be improved to help users accurately identify distances and altitudes.

Smartphones Are an Appropriate Delivery Technique The visualization was implemented on smartphones to leverage a platform widely accessible to students. The experts strongly agreed that the devices are appropriate for GA weather education. The university thunderstorm expert stated that "the fact this works on a smartphone allows it to be used by the broadest possible audience." Most university undergraduate students (99% in 2016) report owning smartphones [63]. Smartphone-based AR is a common delivery method for educational AR, with review studies reporting between 44% and 60% of AR studies were conducted on smartphone-based AR [50], [59]. For

instructors and students who already own a smartphone, smartphone-based 3D AR is a cost-friendly and convenient way to access training content. Alternative AR devices such as head-mounted displays (HMDs) may be assessed for their costs and benefits to training.

Opportunity for Future Work Although experts agree that the visualization content was appropriate for the learning goals, they suggested areas of future model expansion. The experts suggested adding components to this visualization such as turbulence, hail damage, thunderstorm avoidance, wind shear, and microbursts, as well as developing additional visualizations of organized thunderstorm systems such as squall lines. The experts suggested that weather visualizations could be used for training in multiple ways, not merely for communicating weather theory. They suggested that weather visualizations may improve communication about the weather, weather avoidance, and the impact of weather on flight. Further, they suggested that student interactions could be designed to enhance effective decision making and the consequences of flying into weather.

Interactive print materials can be created by integrating the thunderstorm visualization evaluated in this study into existing printed training materials. The visualization can be digitally placed (overlaid) by inserting AR markers in the text at specific points to provide context-appropriate visual information in the learning environment. The integration of 3D AR content into existing print documents has made representations of natural phenomena more accessible in the classroom [2] and has impacted student learning in other domains [23], [25]. Future work can further assess the impact of interactive print on GA weather education.

Communication about weather avoidance, the impact of the weather on flight, and the consequences of flying into weather may be supported individually through discrete learning activities, or they may be addressed together through more extensive and complex activities. One promising approach is to create 3D AR scenario-based activities. Scenario-based activities have been used to teach student pilots about weather technology and are expected to be effective teaching tools for weather education [19], [20], [37], [64], [65]. Future work can develop 3D AR scenario-based activities with 3D content, animation, and interactivity to help instructors and students communicate various aspects of aviation weather in training.

Conclusion

This study found preliminary evidence that the 3D AR thunderstorm visualization could effectively enhance GA weather education. Student's knowledge of thunderstorms increased after using the visualization to explore the dynamics of the thunderstorm lifecycle and various aspects of thunderstorms. The communication of thunderstorm theory was supported by the animation and interactivity of the visualization. Students interacted with the visualization to layer and animate information about various hazards such as wind patterns, wind speeds, precipitation timing, movement distances, icing, and temperatures. The animation helped students learn about the dynamics of thunderstorm development. In other domains, the communication of theory may also be supported with animated, interactive 3D AR learning objects. Experts felt that the visualization could effectivity enhance weather education in aviation. They felt that the learning experience met their expectations of what they wanted to communicate about thunderstorm theory. The interactivity may help instructors communicate various aspects of thunderstorms to students. Finally, participants rated the application as usable with an appropriate level of workload in completing tasks.

Future research can investigate the beneficial impacts of integrating 3D AR weather visualizations into established GA weather training curricula. For example, these visualizations may impact the development of mental models, which is a concern in the study of communication and cognition [66]–[68]. In the past, interactive videos and AR support systems have helped workers develop mental models of tasks [26], [47]. Animated 3D AR weather visualizations may also help students develop robust mental models of weather phenomena and avoidance. This benefit would be appealing because the development of robust mental models could be an important component of learning to make good weather-related decisions in flight [48], [49]. A longitudinal study could also be conducted to study the impact of using these visualizations on students' retention and recall. Beyond education, AR visualizations could be used to support weather-related decision making. For instance, 3D virtual representations of real-time weather could be used in the cockpit to support pilot decisions related to weather.

Finally, we note the challenges and limitations encountered in the development of this 3D AR thunderstorm visualization.

1. Real thunderstorm data with enough detail to inform thunderstorm modeling were difficult to obtain. Our team generated approximate thunderstorm data to model a generic thunderstorm's cloud movement and wind drafts during the cell lifecycle. The difficulty of obtaining actual data means that additional efforts to visualize weather may also use approximated data.
2. The amount of work required to produce the 3D visualization was high and likely higher than the production of paper-based 2D representations. Specifically, achieving realism in visualization requires specialized knowledge in computer graphics, modeling, and visualization.
3. To make the 3D AR experience available to a broad demographic in the GA community, we had to balance the ability of the 3D AR to be used as a stand-alone experience versus integrating the experience into existing training materials, such as a textbook, which limits the number of people who will access it.
4. The number of participants in this preliminary evaluation was small. Future work will evaluate this approach in a larger summative evaluation with beginning aviation students.

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