Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #46557

Best Practices for Developing Virtual Reality Education Simulations

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Abstract

In recent years, virtual reality (VR) has seen an increase in usage in schools as a novel way to provide students with immersive learning experiences. Through the use of VR, students can explore real and abstract concepts that fall under the DICE categories (Dangerous, Impossible, Costly, or Experiential)– concepts that cannot be easily taught with traditional methods. With VR, instructors can expose students to new learning opportunities. However, developing a customized VR learning simulation is a time-intensive process that requires careful design decisions early on, as these choices can be difficult to revise later. The end product must not only be engaging and informative, but also accessible to a wide audience. Moreover, given the significant investment in both VR headsets and development time, it is essential that the final product justifies the use of VR as a medium.

This paper examines the design challenges of developing an educational VR simulation from scratch, with a strong focus on pedagogical, accessibility, and technical implementation considerations. This paper offers a series of best practices for creating effective simulations for classroom use, drawing from real-world case studies from multiple STEM fields to illustrate practical applications. The strategies and lessons learned serve as guidelines for designing other VR educational simulations and are applicable to a variety of subjects. The findings are relevant to educators and developers alike and contribute to the broader conversation on integrating VR into the classroom.

Introduction

Virtual Reality and its Use in Education

Virtual reality (VR) is an immersive technology that allows users to interact with and experience digital environments as if they were real. Though most commonly used for entertainment, VR has also seen applications in military training, commercial, industry, and educational use [1]. VR devices come in various forms, such as CAVE systems, head-mounted displays (HMDs), and desktop variants. HMD headsets are the most recognized type of mainstream device and have shown better performance by learners over CAVE systems, desktop variants, and non-VR users [2, 3]. Among HMDs, there are two types: tethered and untethered. Tethered headsets require physical connection to a computer for processing, while untethered headsets can function on their own. Commercially available HMDs– both tethered and untethered– such as the Meta Quests [4], HTC-Vive [5], Samsung Gear [6], and ClassVR [7], have seen demonstrated effective use in classrooms for a variety of subjects. However, this paper focuses specifically on the development of educational VR simulations for untethered HMDs, as they provide the best balance between immersion and cost-effectiveness.

Concerns for Use

Though VR has a transformative potential for education, its integration into classrooms faces several challenges. One significant issue is the limited selection of available educational content. Currently, VR educational use cases are primarily concentrated in fields like medicine, where simulations of surgeries or anatomy have clear applications [8]. Expanding to cover a broader range of subjects often requires custom-built simulations, as existing content is often unavailable or non-existent. This reliance on custom solutions presents a substantial barrier for educators, as creating VR experiences demands considerable technical expertise, time, and financial resources.

Many custom VR builds for education have been criticized for being experimental in nature, often lacking a foundation in sound pedagogy [3, 9]. This critique highlights the need for collaboration between educators and developers to create pedagogical VR content. Without aligning simulations with evidence-based teaching methods, there is a risk that the technology may not effectively support learning objectives.

Another critical issue is that use of VR can cause cognitive overload, particularly in new users. Cognitive overload occurs when the learner's working memory is overwhelmed by essential and extraneous cognitive processing [10]. In other words, the combination of information processing and load induced by learning tasks can affect a students' ability to process new information and long-term memory [11]. Poorly designed VR experiences– such as cluttered user interfaces, excessive stimuli, or unclear objectives– can overwhelm the user, thus decreasing effective learning [12]. Therefore, careful design choices must be made to support learning.

Accessibility is often overlooked as a concern for using VR in classrooms [13]. Ease of use can be addressed with general game design principles, but special accommodation for diverse needs and concerns for motion sickness must also be accounted for. Educators and developers should ensure that VR tools are accessible and effective for all learners, regardless of their individual needs.

To address the challenges listed above, careful planning and preparation are essential both during the development of VR simulations and their implementation in the classroom. Educators and developers must collaborate to design experiences that are pedagogically sound, appropriately immersive, and accommodating to users' needs. This paper aims to provide a framework for navigating these concerns by offering educators and developers with a series of best practices for creating effective VR learning simulations.

Design Challenges for VR Development

Identifying Proper Use

It is critical to understand how to maximize the benefits of VR before educators invest in technology and development. VR potential is best realized when applied to topics that align with the DICE framework: Dangerous, Impossible, Counterproductive, and Expensive [14, 15]. This framework applies broadly to all VR applications, including educational usages. Consider several examples of effective VR topics for education: reducing the dangers of an introductory course to welding [16]; visualizing impossibly small atoms and interactions [5]; helping individuals overcome stage fright and improve presentation skills, without needing a large audience (which may be counterproductive to the audience's time) [17]; or allowing a class to visit the Mona Lisa at the Louvre, without incurring travel and ticket costs [18]. Conversely, topics outside the DICE categories may be better suited for traditional teaching methods, making their adaptation to VR less effective and an unwise use of the medium.

Before fully committing to VR, it may be worthwhile to consider an alternative: augmented reality (AR). AR is the layering of digital information over real-world objects, which allows users to interact with the real and digital worlds. By contrast, VR deals with interactions in the digital world only, and is concerned with virtual objects in a virtual space [19]. By this definition, AR has several unique advantages, such as the ones listed in Table 1, in comparison to VR that may align better with educational objectives. For example, scenarios requiring interaction with the real world– such as training exercises– can use AR overlays to save the effort of recreating the environment in VR. Interaction with the real world allows students to take notes during the experience and collaborate with each other in real life. On the topic of environments, rendering an environment in VR that is not conducive to the educational goals may be a distraction for some users and contribute to cognitive overload. If the surroundings of the user do not contribute to learning, they may be seen as extraneous input, thus suggesting use of AR instead.

As an additional benefit, AR applications can run on mobile devices such as phones or tablets, reducing the cost of hardware. However, AR is not suitable for rendering large objects to scale, as they may exceed the physical boundaries of the real world. While AR reduces the risk of cybersickness, it comes at the expense of a fully immersive experience that only VR can offer.

Table 1: Advantages of augmented vs. virtual reality

Augmented Reality	**Virtual Reality**
Information is overlaid in a physical space	Information is rendered in a virtual environment
Environment is not important or a readily-accessible location in the real world is used	Environment is difficult or impossible to access in the real world but crucial for situational learning
Digital objects fit within the confines of the physical space	Digital objects can be rendered at any scale
Interactions are performed in the digital and real world	Interactions are fully digital
Note taking enabled	Physical note taking requires pausing simulation
Real and digital collaboration with other users enabled	Digital collaboration with other users enabled
New users less prone to cybersickness	New users subject to cybersickness

Two case studies are presented in this section to highlight valuable use of AR or VR as a medium. In the first case, researchers from San Diego State University use a custom AR application to teach university students about electric fields, a spatial concept that is difficult to convey in a 2D space [20]. For this use, the focus is on the electron and its field; the virtual environment does not matter, so it has been excluded. Instead, the model is projected into the space in front of the students using iPads, and students collaborate in pairs during the activity. Though mobile handheld devices are generally more readily accessible than head-mounted displays, the researchers note that prolonged use led to complaints of arm fatigue from users.

The second case analyzes ScienceVR, a VR chemistry lab simulation designed for STEM learners. The creators state that the realistic laboratory environment "enables learners to see themselves in an authentic-looking lab," thus highlighting the importance of a higher degree of immersion [21]. Attempting to translate this experience to AR whilst maintaining environmental context would have required more real-world planning (such as the use of a real laboratory). However, creators cite the cost of maintaining a real laboratory and general lack of access to a lab as a reason for simulating the environment in VR.

Best practice:

- Identify topics that fall into the DICE framework to justify the use of VR.
- Carefully weigh the benefits of teaching in AR, VR, or sticking to traditional methods before making a commitment.

Identifying Pedagogy

A common critique for VR use in education is that pedagogy comes second to the novelty of the technology [9, 21]. In teaching, pedagogy should be a priority, no matter the medium. Therefore, it is essential that instructors understand what educational theories align well with VR. The most commonly cited theories are constructivist in nature; that is, focused on how personal experiences relate to new knowledge in order to construct meaning [9, 22]. Robust VR design also incorporates cognitivist ideas including the cognitive theory of multimedia learning and cognitive load theory, which is particularly relevant for developers and discussed in a later subsection. For educators, constructivist theories such as experiential learning theory, situated learning theory, and guided discovery learning theory have great potential to be enhanced by VR.

Experiential learning theory states that learning occurs through a cyclical process of concrete experiences, reflective observation, abstract conceptualization, and active experimentation [23]. Experiential learning has the most potential to benefit from VR, as engaging experiences can be simulated through virtual interactions [24]. Situated learning theory posits that knowledge is extracted from the social, cultural, and physical context in which it resides [25]. Because VR offers a sense of presence and immersion, virtual environments can be constructed to provide rich situational context for learning. Finally, guided discovery learning theory claims that learners who explore and draw conclusions on their own– with limited help– develop a sense of self-efficacy that reinforces learning [26]. Less structured, open-world VR simulations can foster a discovery-based environment that can be difficult to recreate in the real world.

Though less common and more difficult to develop, VR also has the ability to support social cognitivist theories that emphasize learning by observing and imitating the actions of other individuals [13]. Social interaction can be accomplished through multiplayer platforms, depictions of individuals through avatars, or addition of non-playable characters (NPCs). VR can be used to teach about empathy, encourage collaboration, and recreate social situations [14].

An example of a simulation that incorporates experiential, social cognitivist, and inquiry-based learning (similar to discovery learning) can be found in a study by Petersen et. al, who created a virtual field trip simulation to teach middle school students about climate change [6]. Results from their study show that students showed improvements in self-efficacy, interest, and knowledge in climate change. Additionally, students showed increased intention in pursuing STEM after observing a climate scientist in VR. By matching educational theory to the designed VR activity, researchers were able to create a meaningful experience for their students.

In this paper, it is assumed that the instructor and developer are two different entities, although in some cases they may be the same person. Under the assumption that the two roles are separate individuals, it is strongly emphasized here the need for explicit, well-articulated communication between the two. The instructor's responsibility lies in defining clear learning objectives grounded in pedagogy, while the developer's role is to create simulations that effectively support those objectives. The instructor and developer should work together to define clear expectations and maintain communication during development. Without a shared understanding of goals and constraints, the simulation may not achieve meaningful learning outcomes.

Best practices:

- Lay out explicit instructional goals tied to established educational theories.
- Lay out explicit simulation design criteria for the developer to meet the instructional goals.

Creating the Virtual Environment

Multiple VR platforms exist that range from beginner-friendly tools to advanced professional game engines. For those new to VR or with limited technical skills, platforms like CoSpaces provide an accessible way to create interactive 3D and VR content. CoSpaces, which has already been demonstrated in educational settings [7], uses a simple drag-and-drop interface and offers basic coding options like block-based programming. Beginner platforms eliminate the steep learning curve, but offer limited capabilities. For more advanced developers, professional-grade tools like Unity and Unreal Engine offer extensive features and are capable of creating highly detailed and interactive VR simulations. These platforms allow developers to use programming languages such as C# (Unity) or Blueprint scripting and C++ (Unreal) to build custom functionality; simulations can then support realistic physics, complex animations, and spatial audio. Though these tools require more technical expertise, they are well-documented in their respective communities.

Once the platform is chosen, developers can then begin to assemble the virtual world. Assets used to populate the build– including 3D objects, visual effects, sound effects, and scenery– can be custom creations or acquired. Custom assets allow for greater personalization, but complex models can add significant development time. To minimize costs and streamline production, it is highly recommended to utilize free, open-source assets wherever possible. Alternatively– assuming a sufficient budget exists– developers may opt to purchase assets to save time.

Developers have the option to create the virtual world rooted in fantasy, realism, or a combination of the two. Several such design considerations are presented in Table 2. For education purposes, the required level of realism depends on the educational objectives and reliance on situational learning. On one hand, realistic renders mirror the real world more accurately but may be more computationally expensive to develop. On the other hand, a fantastical representation can still effectively convey key concepts at a lower computational cost, making it suitable for scenarios where environmental accuracy is less important. This idea also extends to user interactions, which can mirror natural, intuitive hand motions or require controllers or learned movements. By balancing realism with practicality, this reduces unnecessary development complexity.

Table 2: Example of design choices when constructing the virtual world.

	Object	**Behavior**	**Interactions**
Realism	• Real setting • Photorealistic objects	• Gravity • Expected behaviors	• Hand manipulation • Natural gestures (grabbing, pinching, waving, etc.) • Continuous locomotion (i.e., walking)
Fantasy	• Imaginary setting • Stylized objects	• No gravity/ floating objects • Special visual effects	• Controllers/raycasting • Unnatural, learned gestures (hand signals) • Teleportation

Consider two examples of VR learning simulations. IMMERSE, a language learning app available on the Meta Store, teaches users language skills through social interactions [27]. Here, learning is primarily facilitated by interactions with other individuals, and the environment is arbitrary; as such, the environment and avatars are constructed from simple models. In another example, a highly realistic virtual operating room and patient was created to train surgeons in laparoscopic surgery [28]. Development went one step further, with the incorporation of a custom haptic feedback device that simulates tissue. In this case, realism in object, behavior, and interaction is critical, as the simulation's accuracy directly impacts the surgeon's ability to perform in real life.

Perhaps one of the most crucial stages to development is beta testing. Beta testing allows developers to catch and address bugs, inaccuracies, or other flaws in the build. Developers should thoroughly test their own product, but it is equally important to involve educators who can provide feedback on whether the simulation aligns with educational objectives. Most importantly, however, students—the end users—should participate in beta testing, as their perspective provides unique insights. Game development is an iterative process, and it is important to test often with a diverse range of users to optimize the final product.

Best practices:

- For beginner developers, consider low-fidelity platforms like CoSpaces to create simple builds.
- For advanced developers, use a well-documented game engine such as Unity or Unreal.
- Take advantage of free or low-cost digital assets (such as 3D objects, avatars, and environments) to significantly reduce modeling and world-building time.
- Determine the level of realism required to support learning based on the instructional goals.
- Beta test frequently with students and adapt to feedback.

Accommodating User Needs

Without some form of guidance in the virtual world, new users can experience cognitive overload, which hinders learning [29]. Tutorials should be included for users to familiarize themselves with the controls and situation before engaging with more complex tasks. To further ease the learning process, content should be broken up by structuring it into levels or scenes that build on prior knowledge according to scaffolding principles [24]. This approach allows users to interact in manageable, progressive increments. Additionally, incorporating checkpoints and feedback within each level can let users keep track of progress and provide them with a sense of accomplishment that reinforces their understanding. Tutorial and scaffolding techniques create a supportive learning environment that minimizes frustration for users.

In order to enable the feeling of immersion without causing cognitive overload, it is important to find a balance between extraneous details and essential materials. There are unlimited creative possibilities with VR, so it is easy to overwhelm users (and developers too, for that matter). For multimedia learning mediums such as VR, cognitive overload can be mitigated by adhering to five principles originally proposed by Mayer in [10]. Definitions and applications are summarized in Table 3.

Table 3: Applications of multimedia learning principles to VR development.

Multimedia Learning Principle	**Application to VR**
Coherence Principle: Exclude extraneous material	Simulate what is necessary, avoid wasting time on nonessential details.
Signaling Principle: Use cues to highlight essential material	Use visual (special effects, contrasted colors, bolded words) and audio (sound effects) cues to guide the player in the right direction.
Redundancy Principle: Graphics and narration are more effective than graphics, narration, and text	Use voice overs to accompany visuals and make the presence of on-screen text optional.
Spatial Contiguity Principle: Present corresponding words and pictures close to each other	Consider the spatial placement of informative displays carefully, especially when viewed from alternative vantage points in 3D. Consider using a "billboard" technique that swivels a 2D display to point perpendicular to the viewer.
Temporal Contiguity Principle: Present animations and narration simultaneously	Use voice overs to accompany and describe animations.

The author of this paper suggests that application of the redundancy principle be modified to account for accessibility issues. Specifically, users with limited hearing or in loud settings (such as a classroom) may benefit from subtitles or other text along with narration and graphics. To account for as many user needs as possible, it is best to give users the option to enable supplementary text as necessary. The idea of customizability for accessibility also extends to other VR fundamentals, like controls for sound and music, options to choose between interaction methods (i.e. using hand gestures or controllers), or modes of locomotion (i.e. walking or teleporting). These additional features may increase development time, but should be strongly considered; not only do they accommodate users with physical disabilities or sensory impairments, but they also offer flexibility for different users' preferences and comfort levels.

Comfort is an important factor of consideration when designing a simulation. In VR, comfort can be thwarted by a phenomenon referred to as cybersickness, also known as simulator sickness. Cybersickness is a type of motion sickness with similar symptoms and effects: dizziness, nausea, headache, disorientation, to name a few [19]. It can be difficult to predict who will experience cybersickness, but it is more likely in those who experience regular motion sickness [30]. Cybersickness is caused by simulated motion, but there are several design decisions that can be made to reduce potential causes, some of which are presented in Table 4 below.

Table 4: Suggestions for avoiding common factors that cause cybersickness.

Causing Factor	Suggestion
Duration of use	Limit extensive VR activity to no more than 30 minutes. For longer experiences, consider inducing breaks by having the student complete a worksheet or other real-world activity.
Sudden acceleration	Reduce walking speed, disable jumping, and use smooth motions to gradually accelerate the player.
Unanticipated movement	Fade in and out between scenes/teleporting rather than instantaneous change. Avoid unnatural movements or overriding the player's camera control.
Smooth locomotion	Simulate the natural movement of the head by bobbing while walking or use teleportation methods instead.
Narrow field of view (FOV)	Increase the player's camera FOV or induce blur (vignetting) around the peripheral of the camera's view.

Unfortunately, not all users can experience VR the same way. For some users, severe cybersickness can make VR experiences intolerable, while for others, standard VR devices may be inaccessible due to physical or technical limitations. In order to offer students that fall into these categories comparable learning opportunities, it is recommended that educators prepare a non-VR activity that closely matches the VR experience as much as possible. This can be in the form of a video, supplemental reading, or another traditional method as long as they adhere to the same learning objectives. Accessible alternatives are not something traditionally considered in the literature, but by proactively addressing these challenges, educators can ensure that all students have access to comparable learning opportunities regardless of ability to use VR.

Best practices:

- Include tutorials within the simulation to allow users to familiarize themselves with the controls.
- Scaffold content by incorporating a level or scene structure.
- Make conscious design decisions to avoid overwhelming the user.

- Give users the option to control sound, subtitles, music, etc. so that they may adjust for personal preference.
- Make conscious design decisions to avoid inducing cybersickness.
- For students with special requests, provide a non-VR activity that closely matches the VR experience in learning objectives.

Implementation

Unlike traditional simulations designed for a single player in a private setting, implementation in classrooms must accommodate multiple users sharing the same physical space. Simultaneous users in a limited space raises several unique design constraints. For example, player movement in the virtual world should be conducted by hand or controller input– not by movement in the real world. Real movement can be further prevented by the use of stationary player boundaries (virtual borders that restrict real movement within a fixed space) rather than large room-scale setups that enable physical walking. Allowing players to walk freely in the real world increases the risk of collisions with each other or with objects. Another example for densely-packed classrooms is overlapping audio, which can be distracting. Incorporating subtitles or other text-based cues can reduce reliance on audio and minimize extraneous noise. A dedicated space for VR activities can relax these constraints, but available space requires additional resources and logistics.

Creating a safe and effective learning environment is the main goal of successful implementation. To ensure safety, instructors should warn students about the symptoms of cybersickness and educate them on ways to reduce discomfort before use. An example of such instruction is given in the infographic in Figure 1. The instructor should also actively monitor students for proper device use, signs of cybersickness, and to prevent collisions or accidents.

Figure 1: Instructions for Meta Quest 2 users on how to reduce the likelihood of cybersickness.

To ensure effective learning, educators may wish to present pre-requisite learning content in real life before a VR activity, as this can reduce the cognitive overload while learning in VR [6]. This pre-simulation context can prepare students with foundational knowledge and address additional learning targets not covered by the VR activity. Additionally, instructors should familiarize themselves with the VR devices and simulations in order to be prepared to troubleshoot technical difficulties. Finally, devices should be prepared with downloaded versions of the simulation and charged ahead of time to maximize productive class time.

Best practices:

- For classroom use, make design decisions that enable multiple users in a constrained space.
- Educate students about cybersickness and prevention methods before use.
- Have instructors provide pre-requisite learning materials before introducing students to VR.
- Have instructors become familiar with the simulation in case of troubleshooting.
- Prepare devices for use beforehand to maximize productive class time.

Practical Application: Aeroverse Module A

Aeroverse was an experimental course conducted by the Aeronautics and Astronautics department at the Massachusetts Institute of Technology and will be used as an example of these best practices put into action. Aeroverse featured six total classes; three main themes in aerospace engineering were covered, split between three weeks. For each class, all students were given a lecture introducing key concepts related to the topic, then split into two groups to complete the following lab activity in either VR or non-VR. Groups then rotated, performing half of the class activities in VR and half in non-VR. A summary of the course layout is given in Table 5. The purpose of the split was to compare the performance of the two groups; results can be found in [4]. Importantly, the students in the course were majority inexperienced VR users who had never used a Meta Quest 2 before.

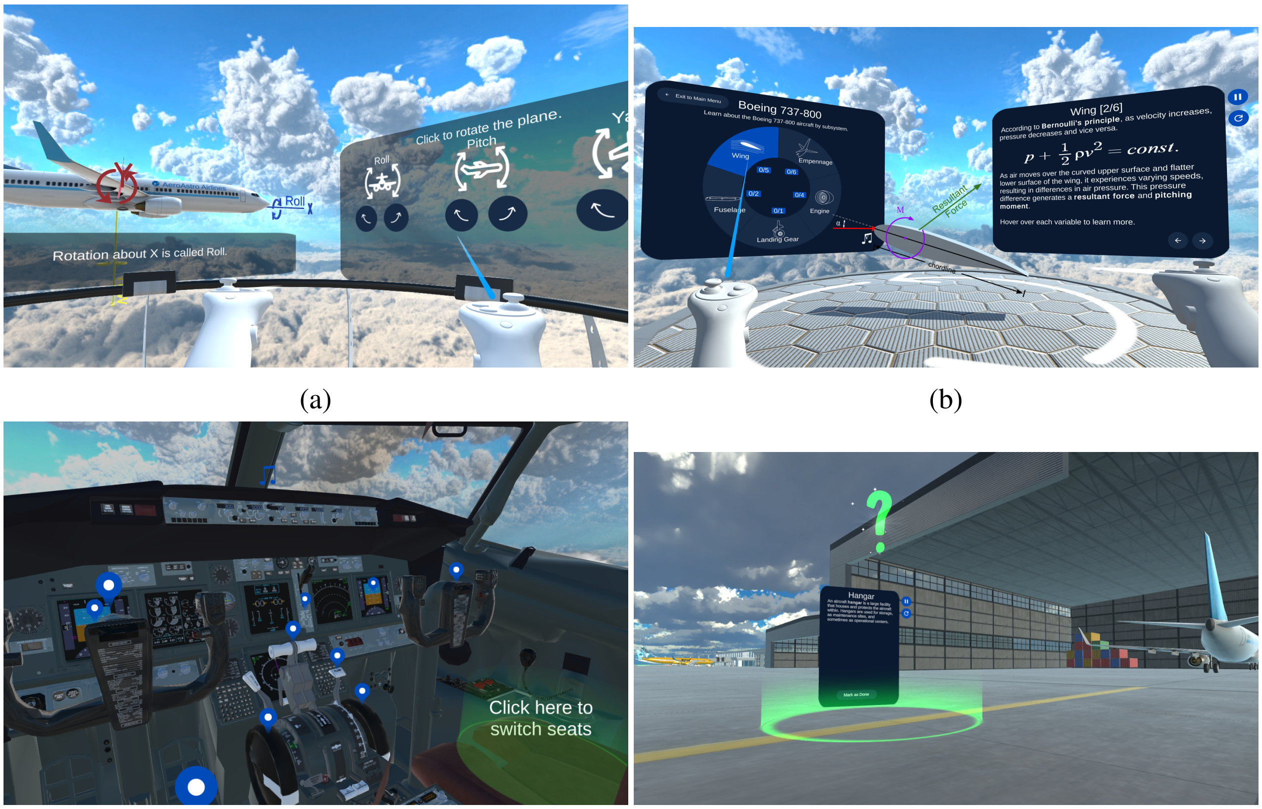
Table 5: Outline of the general course structure for Aeroverse.

Theme	Module Nickname	Description	VR Group
Aircraft Week	Module A: Explore a Jet Plane	Custom module	Group 1
	Module B: Fly a Jet Plane	Microsoft Flight Simulator	Group 1
Spacecraft Week	Module C: Explore Mars with a Remote-Controlled Vehicle	Custom module	Group 2
	Module D: Explore Mars with an Autonomous Vehicle	Custom module	Group 2
Astronaut Week	Module E: Human-Machine Interactions	Mission: ISS scavenger hunt	Group 2
	Module F: Humans in Space	Mission: ISS scavenger hunt	Group 2

The author of this paper was affiliated with the creation of the first module in the series, referred to as “Module A: Explore a Jet Plane.” Specifically, Module A will be used as the practical application case for the best practices listed in the previous section. Note that this paper is a reflection of lessons learned from the development of Module A (and other subsequent simulations), so not all best practices were applied at the time of creation.

Identifying Proper Use

Module A contained four scaffolded "scenes," which the user can select from the main menu. Each scene is separate from each other, and players receive a confetti cue upon completion of a scene to signal when the scene is completed. Figure 2 shows the content of each scene, and Table 6 lists the matching learning objectives and expected outcomes.



(a) (b) (c) (d)

Figure 2: (a) Game play from the Intro to Flight scene. (b) Game play from the Discover an Airplane scene. (c) Discover a Cockpit scene. (d) Explore an Airport scene.

VR was chosen over AR because understanding the scale of the airplane and the spatial layout of the cockpit and airport was crucial to the learning experience. Taking students to an airport and allowing them to physically walk around would have been logistically challenging and counterproductive, as would having each student sit in a cockpit one at a time. Additionally, viewing an aircraft from all angles is difficult to achieve in a real-world setting, and allowing students to demonstrate roll, pitch, and yaw with a responsive aircraft would be dangerous. Instead, all of these activities were made possible by VR.

Identifying Pedagogy

Experiential learning was exercised by letting users control the roll, pitch, and yaw of the plane in the first scene. The subsequent three scenes are based on guided discovery, in which students can explore select components signaled by markers in no particular order at their own pace. Finally,

Table 6: Playable scenes within Module A and their associated learning objectives and outcomes as defined in the course syllabus.

Scene	Learning Objective	Learning Outcome	Scene Description
Intro to Flight	Understand basic principles of aerodynamics in the context of a fixed-wing aircraft	Predict the changes in airflow and resultant flight behavior available from select sub-systems of the aircraft	Interactive presentation where users visualize the forces of flight and control the plane's roll, pitch, and yaw with responding control surfaces
Discover an Airplane	Understand basic principles of aerodynamics in the context of a fixed-wing aircraft Understand the basic layout of a jet engine powered fixed-wing aircraft	Identify various subsystems of a jet-engine powered aircraft Identify components within select subsystems of a jet-engine powered aircraft Assign function to components and to subsystems of a jet-engine powered aircraft Predict the changes in airflow and resultant flight behavior available from select sub-systems of the aircraft	Guided discovery of the main subsystems of an airplane and their constituent parts, introduction and 3D visualization of forces on an airfoil
Discover a Cockpit	Understand the basic cockpit controls of an airplane	Identify components within select subsystems of a jet-engine powered aircraft Assign function to components and to subsystems of a jet-engine powered aircraft	Guided discovery of the parts of a glass (modern) and analog (traditional) cockpit and their relation to control surfaces
Explore an Airport	Understand the basic layout of an airport from a pilot's perspective	Identify and describe the key components of an airport Describe how airport space is allocated (for take-off/landing, gates, hangars, etc.)	Guided discovery of key buildings and components of an airport, passive presentation of an airplane during taxiing and takeoff

the Discover a Cockpit and Explore an Airport scenes benefit from situational learning, as the learner is placed in a digitized version of the real setting at a 1:1 scale. Instructors of the course provided input to the learning objectives and outcomes listed in Table 6. The contents of each scene were created to meet objectives and expectations, which was further supplemented by the lecture provided to students before the lab activity.

Other features were added for pedagogical needs. Uncommon or new vocabulary words are signaled by being underlined and bolded. When users hover over the words, definitions appear above the word. Similarly, users can hover over any variable in an equation to see what that variable represents and the units it is measured in. A summary of new words in a dictionary view is available in the main menu scene for quick reference if the student wants to look up a word without replaying a scene. Finally, visual cues were added to signal what is interactable and what has already been interacted with to ensure that no stone was left unturned. A screenshot from example game play is shown in Figure 3.

Figure 3: Additional game play of the Discover an Airplane scene with interactive definitions.

Creating the Virtual Environment

Module A was created in Unity using a mix of free and premium assets. The virtual environment was designed with realism in mind, though the interactions are fantastic. Environmental accuracy for the Discover a Cockpit an Explore an Airport scenes were desired, as situational context influenced how the information presented was learned. Meanwhile, controller-based interactions were chosen for accessibility considerations (see next subsection) and for ease of interaction at a distance given the large scale of the virtual environment.

To take advantage of the imaginative affordances of VR, method of player movement was explored and varied for each scene depending on the requirements for that scene. In hindsight, keeping the interactions consistent and simplified would have been less confusing for the user, albeit at the expense of novelty. In the Discover an Airplane scene, players can fly around the life-size airplane and rotate it to inspect individual elements up close or far away. In the Discover a Cockpit scene, players are immobilized and fixed to the pilot or co-pilot's seats and can teleport between the two. Locomotion was restricted here, as other vantage points within the cockpit would have been detracting from the experience. In the Explore an Airport scene, players can teleport between locations of interest at a to-scale airport. In the first release of this module, players had unconfined access and could walk around the airport. However, given the maximum walking speed of 1 m/s (any more was disorienting) and the sheer scale of the airport, the method of motion was changed to teleportation as players wasted too much time slowly walking around.

During initial development, feedback was garnered from three rounds of volunteer beta testers unaffiliated with the course. Feedback was also collected from students during the course and applied after the course was over.

Accommodating User Needs

Before accessing the main menu, the user is presented with a very basic tutorial on how to point and select objects with the controller. This tutorial, and all subsequent tutorials, must be physically acknowledged before proceeding to the level. During beta testing, it was found that if the tutorial were not forced, users would ignore it entirely and then become confused on how to interact with the scene. Because every scene had slightly different interactions, it was essential that the user understand and acknowledge the rules before proceeding.

Traditional systems split player movement (i.e. walking) and camera movement (i.e. turning) between the left and right controllers, but for Module A both movement and camera control were mapped to one controller, then duplicated for both. In this fashion, interaction could be performed using only one controller instead of both in tandem. For some users, using both controllers was a physically imposing task, so the option to only use one provided more accessibility. However, the option to switch between two-handed controls and one-handed controls would have been preferable.

For audio options, background music is featured in all scenes, but a toggle option is provided for user preference. Button selections are confirmed with both visual (color change) and audio (clicking sound) feedback. Informational text is displayed in large font and accompanied by an automatic voiceover. Users have the option to play, pause, or restart the voiceover, but the text remains. Though the redundancy principle discourages the use of both text and speech, the text was necessary given that our users were close together in one room and could hear overlapping audio from nearby neighbors. Moreover, the use of text enabled the definition-on-hover feature as an additional layer of interaction shown in Figure 3.

Countermeasures were taken to reduce causes of cybersickness. For example, the user's vision fades in and out when teleporting and entering new scenes to prevent visually jarring changes. Movement is restricted to a slow pace, and extraneous movement is replaced by teleportation. Some scenes were decreased in complexity to increase framerate, as some of the 3D models used were computationally heavy and not optimized for VR use. In addition, during the lab, students were given formative assessments to complete on their laptops. This was partly to engage thinking and partly to provide a break from using the headset, as the total simulation time exceeded the recommended 30 minutes.

Before VR use, students were given the instructions seen in Figure 1. Despite these precautionary measures, 7 out of 15 users reported at least mild symptoms, but none significant enough to stop the simulation. This number may seem high, but recall that the majority of users were inexperienced. Nonetheless, further measures against cybersickness could have been taken, such as removing the flying ability in the Discover Airplane scene, extending/mandating break time, or reducing content to reduce simulation time.

If a student had run into issues preventing them from completing the module, they would have been directed to review the materials prepared for the non-VR group. Materials for the non-VR group were created in advance with the same learning objectives as the VR group for comparative purposes, but they also serve as backup resources for the VR group. For this module, backup materials took form as a lecture with accompanying slides.

Implementation

Students who interacted with the VR simulation used individual Meta Quest 2 headsets and were spaced sufficiently far apart to not overlap stationary boundaries with each other. Despite the fact that students were told to set the headset volume to a low setting, overlapping audio could still be heard from nearby neighbors; in this case, in-game text helped differentiate the sound. The TA present ensured that students maintained a safe distance from each other and monitored for signs of cybersickness. Though students had the option to stand or to sit in swivel chairs (for maximum freedom of movement), it was observed that all students preferred to sit when interacting with the simulation. This was likely influenced by their need to interact with their laptops to complete the formative assessment.

A common critique received from feedback after the class was the annoyance in taking the headset off to use their laptop or trying to use their laptop with the headset on. A proposed remedy would be to add a pause feature that activates the device's passthrough mode– which uses cameras to display the outside world within the headset– allowing users to see the real world in their headsets and thus allowing them to take notes. However, this requires choosing a device with sufficient passthrough quality (not the Meta Quest 2), which may be more costly.

Discussion and Future Work

These best practices arose out of the creation of the Aeroverse modules. Improvements can be made to Module A, particularly in terms of accessibility. Future versions would benefit from simplifying controls, additional cybersickness mitigation methods, and including a note taking feature. An individual analysis of the remaining modules in the Aeroverse course is recommended but outside the scope of this paper.

Efforts to expand the use of virtual reality in the AeroAstro department at MIT expand beyond the Aeroverse course. For example, augmented reality alternatives are being considered based on the unique advantages they offer, as described in a previous section. Future modules will incorporate other subjects in aerospace engineering, including system design, launch vehicles, and combustion engines. Creation of future content can use these practices as guidelines to ensure consistent quality.

Conclusion

A series of best practices is presented throughout this paper relating to the planning, development, and execution of an educational VR simulation from both an instructor's and developer's point of view. The best practices, organized by role, are summarized in Table 7 below.

Table 7: Summary of best practices.

Instructor	Developer
• Identify topics that fall into the DICE framework to justify the use of VR. • Carefully weigh the benefits of teaching in AR, VR, or sticking to traditional methods before making a commitment. • Lay out explicit instructional goals tied to established educational theories. • Lay out explicit simulation design criteria for the developer to meet the instructional goals. • For students with special requests, provide a non-VR activity that closely matches the VR experience in learning objectives. • Educate students about cybersickness and prevention methods before use. • Provide pre-requisite learning materials before introducing students to VR. • Become familiar with the simulation in case of troubleshooting. • Prepare devices for use beforehand to maximize productive class time.	• For beginner developers, consider low-fidelity platforms like CoSpaces to create simple builds. • For advanced developers, use a well-documented game engine such as Unity or Unreal. • Take advantage of free or low-cost digital assets (such as 3D objects, avatars, and environments) to significantly reduce modelling and world-building time. • Determine the level of realism required to support learning based on the instructional goals. • Beta test frequently with students and adapt to feedback. • Include tutorials within the simulation to allow users to familiarize themselves with the controls. • Scaffold content by incorporating a level or scene structure. • Make conscious design decisions to avoid overwhelming the user. • Give users the option to control sound, subtitles, music, etc. so that they may adjust for personal preference. • Make conscious design decisions to avoid inducing cybersickness. • For classroom use, make design decisions that enable multiple users in a constrained space.

To conclude, this paper provides insights into the challenges and best practices for developing effective educational VR simulations. By addressing key considerations in pedagogy, development, and technical implementation, it offers practical strategies that can guide both educators and developers in creating immersive learning experiences. The examples from various STEM fields demonstrate the real-world applicability of these approaches, and an in-depth analysis of a practical application was performed for the structure of Aeroverse: Module A. As VR continues to gain traction in classrooms, the lessons learned and strategies outlined here will serve as a foundation for future developments.

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