SpaceVR: Outreach out of this world!

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***Abstract*—Space is the final frontier and engaging people with Space Science through Virtual Reality (VR) is uncharted territory. Enhancing engagement Space Science can inspire students to pursue a career in science, technology, engineering, and mathematics (STEM), giving them the skill set to help solve societal issues. This project has developed SpaceVR, a VR software application designed to enhance engagement of high school students with the Space Science subject. The project furthers our knowledge about science outreach by exploring whether integration of scientific data and the addition of gamification elements to a VR experience enhances user engagement. Within SpaceVR people can learn about solar phenomena by viewing real images of the Sun taken by NASA's Solar Dynamics Observatory (SDO) spacecraft and experience the effects of solar flares. SpaceVR was evaluated at the Victoria University of Wellington Open Day with high school and university students. The results of the evaluation indicated that the experience was enjoyable, and immersive. The usability of the experience was found to be average. Some players found the player activity and tasks disengaging and some found the controls difficult to use.**

***Index Terms*—Virtual Reality, Education, Space Science.**

I. Introduction

A. Motivation

Virtual Reality (VR) experiences exist on a spectrum ranging from purely entertainment through to training and education. Many VR applications exist along this spectrum such as Valve's VR game "The Lab" [1], Christchurch Airport's VR training application [2], and "The Body VR" which teaches students about the biology of human beings [3].

Somewhere in the middle of this spectrum lies VR experiences for engagement and outreach. These experiences are not aimed to train their players in a new field but try to interest them in a topic they have not been exposed to before.

SpaceVR aims to position itself in the middle of this spectrum by providing an engaging outreach experience around Space Science, targeted at high school students. Engaging high school students in Space Science can help inspire students to pursue a career in STEM subjects, giving them the skill set to help solve societal issues.

B. The Problem

The aim of this project is to create and evaluate a VR experience that can be used to engage high school students with the basics of Space Science, in particular, the Sun and Solar Phenomena. There are many resources that teachers can use to teach Space Science, but SpaceVR hopes to create interest in learning about Space Science.

This project was supervised by Alex Doronin (primary), Craig Anslow, Yvette Perrott (School of Chemical and Physical Sciences), and Tulasi Parashar (School of Chemical and Physical Sciences).

Previous research has shown that getting students interested in STEM can be facilitated with VR engagement tools [4]. There are two aspects to the investigation. One aspect is to integrate scientific data into the application to provide a more engaging experience, using data from NASA's Solar Dynamics Observatory (SDO) satellite [5]. Without scientific data, the Sun is visualized by an artist's interpretation. The other aspect of the investigation is investigating if the addition of gamification elements [6], purely narrative, increases the engagement of the experience.

We use D. Gorman et al's [7] definition of engagement as being *the ability of the experience to encourage the users to explore, interact and learn.*

C. Solution

SpaceVR builds off of the SunVR project, a 2022 summer research project that can visualize SDO data in VR. SpaceVR has three deliverables: A desktop VR application, a portable metaquest version of the VR application, and instructions on how to use the application during outreach events.

- A desktop VR application that can be experienced through a Meta Quest 2 VR head mounted display (HMD) has been developed. The desktop application requires a high performance computer to run and the headset must be tethered to the computer reducing its portability. The application features a player tutorial, a guided player activity showing solar flares, and the original SunVR experience is included as a bonus free-play game play mode.
- Instructions for outreach activities were not created as the experience is not yet ready to be used in outreach events.
- A lean version of the experience with reduced capabilities that runs on the Meta Quest 2 directly was created. The lean version is portable, it can be run without needing to be tethered to a high performance computer but has less features to meet the Quest 2's performance constraints. It includes the functionality of the original SunVR application and a single solar event to observe.

D. Sustainability

Environmental and sustainability issues impact SpaceVR. The United Nations has published 17 goals for achieving sustainable development [8] it is important that the solution is aligned with these goals. The existence of SpaceVR serves to further sustainable development goal 4, ensuring inclusive and equitable quality education and promoting lifelong learning opportunities. It achieves this by increasing engagement in Space Science, encouraging students to learn about the subject area by showing Space Science's importance to modern human life. Sustainable development goal 5, achieving gender equality and empowering women and girls, has been factored into SpaceVR by ensuring there is no gender bias in the instructions and activities present in the VR experience. The resources needed to develop VR experiences are significant. A high-end development computer and VR headset requires financial resources to acquire and uses precious metals in the manufacturing process. To align with sustainable development goal 12, ensuring sustainable consumption of resources, SpaceVR will utilize the resources and equipment of Victoria University's Human Computer Interaction (HCI) group [9]. Working with the HCI group allows SpaceVR to be developed and tested by re-using pre-existing resources instead of contributing a larger financial and environmental impact by procuring new resources for the project.

E. Findings

The project goals of incorporating SDO data into a VR Space Science experience and adding narrative to the experience as a game mechanic have both been achieved.

Most participants enjoyed SpaceVR with the positive affect mean score being 3.27 out of 4. This was achieved despite mixed usability scores. The mean System Usability Score was 69, only one point higher than 68, which is considered the minimum score for acceptable usability. The mean immersion score was 2.77 out of 4. 57% of participants had an immersion score above 3. This indicates that the virtual environment was immersive.

Qualitative user feedback analysis indicated that the experience could be further improved with the addition of more game mechanics for the player to learn and master, and more interesting challenges. The user feedback indicates that narrative progression on its own is not a sufficient reward mechanism for the player.

II. Related Work

Existing literature on using VR for engaging in STEM topics was reviewed for insights that SpaceVR could use. Cutting edge work on Sun visualization is reviewed. We also present background on the tools and technology used for SpaceVR.

A. STEM engagement

D. Gorman et al. investigated if engagement in food technology education could be increased with using 360 degree VR videos [7]. The player activity consisted of a non-interactive 360 degree video that demonstrated a food technology lesson such as how to wash your hands correctly. After the lesson, a multi-choice question is shown. Players interacted with the questionnaire and selected lessons using 'gaze tracking', where the player looks at the object they want to select. They evaluated their system during a normal school class with 12 participants. Observations of the participants behaviours were collected and they completed three questionnaires: System Usability Scale and an engagement questionnaire with questions adapted from other studies. They found that the effectiveness of VR in teaching can be increased by giving players time to acclimate to the virtual environment before presenting them with tasks to complete. The authors identified that usability issues occur when the player's actual height does not match their virtual height. They suggested adding gamification mechanics to increase the players focus with the experience. These findings were considered in the design of SpaceVR. They concluded that the usage of VR can make teaching food technology education engaging, fun and motivating. SpaceVR has increased interactivity compared to this work. There are no environmental objects to interact with and menu navigation is performed by stating at the option you want to select for three seconds. In contrast SpaceVR has a 3D environment for the player to move through and interact with using their hands. SpaceVR incorporates a linear narrative and more tasks to complete beyond answering a question at the end of a lesson.

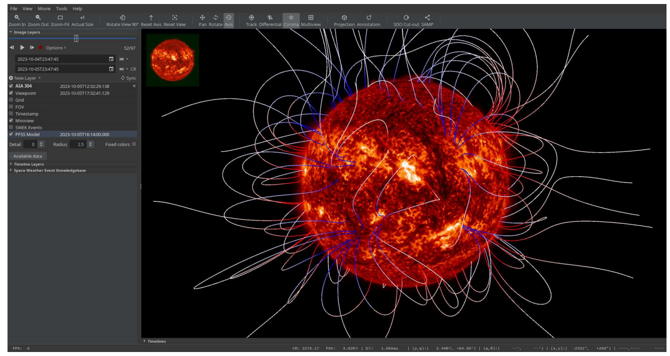


Fig. 1. Helioviewer User Interface [10].

B. Sun Visualization

Helioviewer is a family of applications and services that allows for interactive visualization of SDO data [10]. Helioviewer represents the state of the art for streaming, browsing, and visualizing SDO data. Figure 1 shows the Helioviewer user interface. SpaceVR differs from the Helioviewer solution in its use of VR in the visualization, which can lead to increased immersion compared to a desktop application.

Bringing the Universe to America's Classrooms (BUAC) is a media collection produced by GBH for PBS LearningMedia, funded by NASA [11]. Of interest is the student version of Helioviewer that was produced by BUAC [12]. Student Helioviewer is designed to increase student engagement in Space Science by allowing them to: view SDO data, view solar events, produce movies from SDO data, and create screenshots. SpaceVR also allows SDO data to be viewed but provides a VR visualization while the student Helioviewer visualization is through a website interface. SpaceVR offers player tasks connected by a narrative, going beyond merely viewing The Sun.

C. Tools and Technology

SpaceVR was implemented within the Unity Game Engine. Unity handles low level operations such as rendering and memory management. The design benefited from the use of

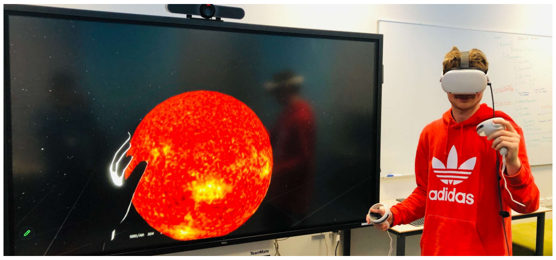


Fig. 2. A prospective student exploring the Sun within SunVR.

Unity as it takes care of low level tasks such as I/O and rendering, allowing the developer to focus on functionality that meets the requirements of SpaceVR. The capabilities of Unity were augmented with several packages shown in Table I. OpenXR was added to enable communication between the game engine and the VR hardware. Since OpenXR is an open standard it can be used to communicate with both the Meta Quest 2 and HTC Vive Pro. This was preferable over the alternatives which can only work with specific vendors: Oculus plugin and SteamVR plugin. Additional art assets were created using Blender [13].

To obtain images for SpaceVR to use we selected the Java programming language to create an SDO image downloading program. This approach was chosen over retrieving data from the Helioviewer service because Unity Game Engine does not have native support for *jpeg2000*, the data format that is returned by the helioviewer API. This also benefited the design as the downloaded images could be cached by the game engine, allowing faster loading times, while data from the Helioviewer service needs to be streamed in each time.

III. Design

We designed a player scenario using the User Centered Design Process and a system architecture to meet the goals and requirements of the project.

A. Goals and Requirements

Seven functional requirements and eight non-functional requirements were defined for SpaceVR. To understand the requirements an explanation of the SunVR project, the prior work which SpaceVR builds upon, is provided. SunVR creates an immersive visualization of the Sun in VR using SDO data. The experience had no narrative or objectives, just 11 solar events, and the ability to view and rotate the virtual sun with a hand grab interaction. Feedback from demonstrations of SunVR indicated that just showing Solar phenomena in VR was not enough to create an engaging Space Science experience. Participants that tried SunVR would would often make comments such as:

> "I can see the Sun. Now what should I do?"

They reported the desire to have some sort of narrative to ground the experience, better instructions, and more activities to complete beyond watching the Sun in VR. Demonstration feedback informed the requirements for SpaceVR.

Functional requirements (FR) are things the system should be able to do. The functional requirements were derived from consultation with clients from the School of Chemical and Physical Sciences who teach Space Science. Functional requirements 5 and 6 were created to address usability issues identified in SunVR.

Req1 **Show a solar flare and its effects**. VR can allow solar phenomena to be shown immersively to the player. This requirement is achieved if the experience visually shows the player a Solar Flare in the SDO data set and at least one effect flares can have on society.

Req2 **Explain what a solar flare is**. It is one thing to view Solar Phenomena, it is another to understand and appreciate what is happening. Explaining what a Solar Flare is can help increase engagement. The requirement is achieved if SpaceVR includes at least one mechanism to explain what a flare is and high level details of how they work.

Req3 **Explain the Solar cycle**. Astronomers have observed that the Sun has a nearly 11 year long cycle of activity. The Solar cycle is observed through variations in the number of Sun spots on the surface. This requirement was dropped as the scope of the project was reduced due to time constraints.

Req4 **Visualize the solar magnetic field**. The Solar magnetic field stretches beyond the Solar atmosphere. The magnetic field can be visualized with Potential-Field Source-Surface (PFSS) Models. Figure 1 shows a PFSS model in Helioviewer. This requirement was dropped as the scope of the project was reduced due to time constraints.

Req5 **Instruct the player how to interact with the game in a tutorial**. One of the shortcomings of SunVR was a lack of instructions during the experience. This requirement is met if there are instructions for moving and interacting with the environment.

Req6 **Communicate required actions to the player**. This requirement arose because it became apparent that participants preferred to be given guidance when using SunVR. The requirement is met if the game has a system that communicates which action the player needs to take at all stages of the experience.

Req7 **Incorporate NASA SDO data in the visualization**. The requirement to use SDO data originated from consultation from the project clients.

Non functional requirements (NFR) are attributes the system should have. SpaceVR's non functional requirements are aimed at providing an easy to use experience that is unlikely to cause cybersickness symptoms. Cybersickness can occur in VR experiences and manifests as symptoms similar to motion sickness [14]. The NFRs are as follows:

Req1 **Game can be completed from seated position**. This requirement arose because the seated position is the least likely to cause cybersickness, players may prefer to play while seated. The SunVR project was designed to be played in a standing position with physical motion. This requirement is implicitly achieved when NFR 4 and NFR 7 are achieved.

Req2 **Provide two alternative locomotion methods**. Teleportation is a common locomotion method used in VR [15].

This requirement was added because some participants were unable to grasp the teleportation method during demonstrations of SunVR, highlighting the need for an alternate locomotion method.

Req3 **Physical interactions with the virtual environment**. This requirement specifies that all environmental interactions can be achieved by tactile interactions (e.g. pushing buttons, grabbing objects, sliding doors). This requirement exists to help keep the experience as simple as possible. The requirement was elicited from a consultation with an exhibit designer at Space Place [16].

Req4 **Player height preference adjustment**. This requirement is to ensure the experience remains consistent regardless of the player's physical height. It was elicited from research that identified variable player height as a potential issue in VR experiences [7]. This requirement is achieved if the game offers systems to compensate for variable player height.

Req5 **Achieve 90 frames per second**. The refresh rate of the display in the Meta Quest 2 HMD is 72Hz. The HTC Vive Pro's refresh rate is 90Hz. Matching or exceeding these refresh rates in the application helps reduce the chances of participants experiencing cybersickness symptoms. The frame rate of the application can be measured using Steam VR's performance monitor.

Req6 **Work with both HTC vive and meta quest controllers**. SpaceVR must compatible with the Meta Quest 2 and HTC Vive head mounted displays (HMDs) because those are the VR devices offered for development by the HCI group.

Req7 **All interactive elements can be reached without physical body movement**. This requirement was inspired by the observation that many participants who played SunVR exhibited Gorilla arm [17]. Gorilla arm is a phenomenon where the player tries to reach out with their hand in the air to interact with the world instead of moving their in-game avatar or by physically moving to reach the object. Gorilla arm can lead to fatigue and frustration.

B. Player Scenario

To achieve SpaceVR's, goals a user scenario was designed for the player to complete. We experimented with the use of narrative as a gamification technique to increase engagement in the scenario. To explore how narrative could be used to increase engagement we considered a variety of scenarios for the player.

Through consultation with a high school Physics teacher two player scenarios were brain stormed. The first was showing the true scales and distances in the Solar system with a large player character that can walk around a 'to scale' solar system. The second was an activity that shows the differences in temperature along the solar atmosphere. During the 2022 ACM ISS conference in Wellington additional scenarios were brainstormed at the game design workshop. A VR escape room scenario where the puzzles require knowledge of the Sun to escape was suggested. Another scenario was a shooting game where the player fires at Solar phenomenon on the Sun to identify them. A 'match 3' style game where the player sorts Solar images was also pitched. During Consultation with an exhibit designer at Space Place a scenario where the player is in a spaceship and performs a spacewalk was suggested.

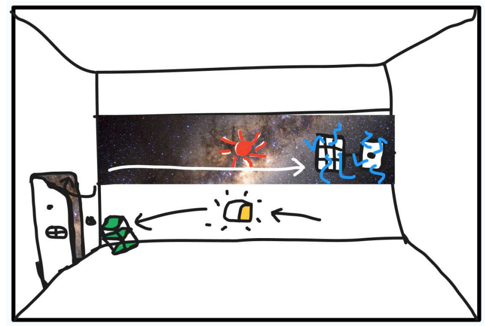


Fig. 3. Storyboard panel for satellite repair sequence.

All of the proposed scenarios seemed promising, we decided to design a tutorial and a player scenario where the player experiences a Solar flare. In the Solar flare activity the player conducts a repair mission on a satellite. These player scenarios were chosen because of their simplicity, allowing for rapid development. Feedback from the tutorial and Solar flare activity would then be incorporated into the development of subsequent player activities.

1) Showing a Solar Flare: Once the player tutorial and Solar Flare activity were decided on, the user experience of SpaceVR was designed through story boards [18]. Story boards show what the player should see in the experience and the actions they should take. We created two story boards for SpaceVR, one for the player tutorial and one for the Solar flare activity. Figure 3 shows the sequence of actions the player takes to repair the satellite in the Solar flare activity, it shows what items the player needs to complete the task and their relative positions. The complete story boards for both the tutorial and Solar flare activity are available in the report appendix.

To achieve FR 1 the Solar flare story board called for the following: a space station environment, beginning the activity with a commentary introduction, letting the player observe SDO images of a Solar flare, observing the flare's effects by watching a nearby satellite malfunction, then conducting a space walk to replace the satellite's circuity, completing the activity. This would also show how flares can affect society as their radiation can affect electrical equipment.

2) Player Tutorial: The player tutorial satisfies FR 5. The player tutorial was modelled after Valve's 2007 game Portal [19] where player progress is blocked by obstacles that require the use of the game mechanic the player is learning to progress. The first mechanic the player learns is movement. The player needs to reach a hammer that is out of arms reach, so they must use a locomotion technique to reach it. The next obstacle is a glass wall that is smashed with the hammer, teaching the player to grab objects in the environment. The final obstacle is a door that can only be opened after the player puts on safety goggles. This obstacle teaches the player about the wearable item system that allows players to wear items

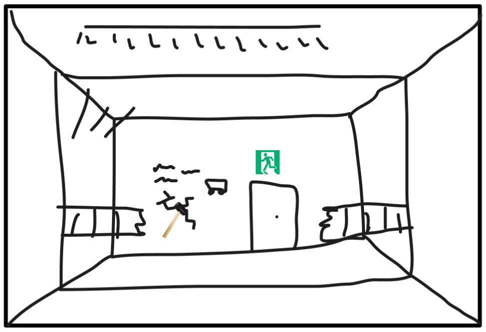


Fig. 4. Storyboard panel for the glass wall obstacle.

on their face. Figure 4 shows the story board panel for the glass wall obstacle, it shows where the glass obstacle should be placed in the environment.

C. System Architecture Design

The design of SpaceVR's player activities called for the following systems:

1) Solar image visualization: SpaceVR uses the solar image visualization technique created by SunVR to achieve FR 1. Figure 5 shows how system components interact with each other. NASA's SDO satellite produces images in a format called FITS. NASA processes these images and hosts the resulting jpeg images on publicly accessible HTTP web server. We decided to use the processed jpeg images instead of the raw FITS data because jpegs are a data format that game engines can use natively. Using the jpegs also avoids duplicating effort in processing the raw data. The webscrapper tool downloads images from a date range and stores them on the development computer. The game engine then imports the images as textures for use in the virtual environment. This design achieved FR 7. The design is ethical because the SDO dataset is in the public domain, usage of the images to create new content is encouraged by the SDO team.

Within the experience, the Sun is visualized using a virtual clock to decide which image to show and a search to find the desired image to be displayed. All SDO images include a timestamp indicating when they were taken a binary search tree is used to facilitate an efficient search. At each update the image that was taken closest to the virtual time is displayed to the player. This process is shown in Figure 6.

The player can alter the virtual time by grabbing and rotating the Sun or by walking around it. When these interactions occur the angular rotation is converted to the number of seconds that would have elapsed based on the Sun's angular velocity and the rotation amount.

2) Player Locomotion: To address the usability problems around locomotion in SunVR, SpaceVR's design offers 3 ways to move through the virtual environment. Teleportation is a common VR locomotion technique where a ray is cast from the controller showing the player where they will move to. Teleportation has a lower chance of causing VR motion sickness at the trade off of being less immersive compared continuous movement. Trigger walking was chosen as an alternative low fatigue locomotion method [20]. Trigger walking works by

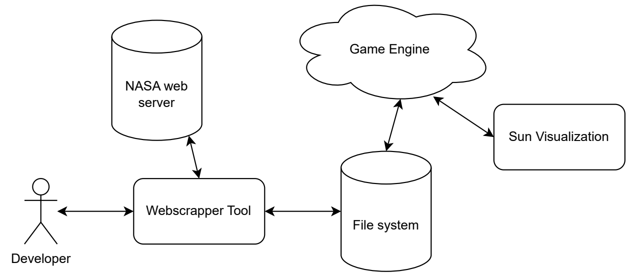


Fig. 5. How SpaceVR obtains SDO images of the Sun.

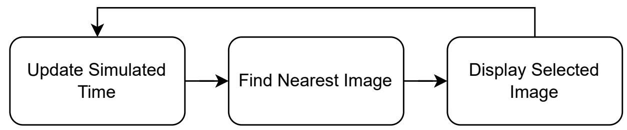


Fig. 6. How SpaceVR displays SDO images.

taking single step each time the controller trigger is pulled. Lastly, the player can physically walk around if they are in an adequately sized play space. Physical movements are matched in the virtual environment.

Adding trigger walking satisfies NFR 2 as the player can choose between teleportation or trigger walking for locomotion depending on their preference. Trigger walking was selected over continuous movement because it is less likely to cause cybersickness symptoms. Continuous movement allows faster locomotion through the environment but teleportation has similar locomotion speed making the trade off acceptable. Both locomotion methods can be used while seated, which satisfies NFR 1. Allowing the experience to be completed from a seated position also improves safety as the risk of falling over is reduced.

3) Tactile game interaction: To achieve NFR 3 we designed the player activities to use physically interactive elements such as the goggles the player puts on their face, doors with handles, and physical push buttons for selecting the level after the tutorial. An advantage of this approach is that players can to rely on knowledge about the real world when interacting with the virtual world. NFR 7 is satisfied by placing the interactive elements in locations that can be reached by the player when in a seated position with the locomotion methods. Players do not have to reach for distant objects they can move their character to the object.

4) Player Height: A system was designed to scale the player's virtual character to a fixed height that is reasonable in the virtual world to satisfy NFR 4. If the player is physically tall then their virtual character would shrink and if they are physically short their character would increase in size. Each player scenario includes the height of the virtual character.

5) Narrative Tracking: To achieve FR 2 and FR 6 a system to track the player's progress through the experience was required. We opted to use an event system where the player's tasks are represented as a series of events. The player causes events to occur, such as breaking the glass obstacle in the tutorial, which causes notifications to be sent to observers that

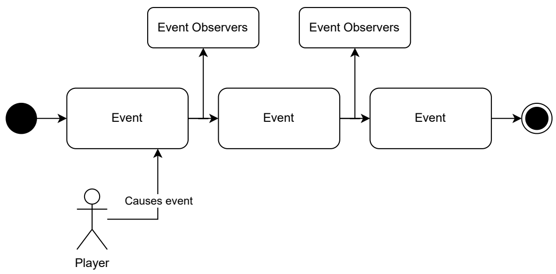


Fig. 7. Events caused by the player are used to track their progress through SpaceVR.

TABLE I
UNITY PACKAGES

Package name	Description
OpenXR Plugin	Enables OpenXR, an open standard for communicating with VR hardware.
Addressables Plugin	Allows dynamic asset loading.
Universal Render pipeline	Controls the rendering workflow. Allows usage of Shader Graph.
XR Interaction Toolkit	Provides a framework for interacting with the virtual environment within VR.
XR Plugin Managment	Manages XR plug-ins for integration with various VR devices.

want to know when the event has occurred.

The next event in the sequence is always an observer to the previous event so it knows when to become available. For example, the airlock in the Solar flare activity won't become available until the space helmet activation event occurs. Other event observers include audio triggers to play sounds, instruction updates that describe the next task to the player, and spawners that create new items in the environment. The event system architecture is shown in Figure 7.

This system was chosen because it facilitated explaining what a Solar flare is after the Solar flare event occurs via an observer. The flare explanation is provided through a text message which was a weak explanation because it doesn't leverage VR's strengths. The system also facilitates communicating the required actions to the player as text instructions can be updated after each task is completed. The system also facilitates long term sustainability of SpaceVR as events can be added and removed without significant reworks of the code base.

IV. IMPLEMENTATION

Unity Game Engine [21] was selected to be used in the development of SpaceVR. Unity was chosen over the other major game engine, Unreal [22], because the SunVR project was already built in Unity. This allowed for code re-use. Using Unreal Engine would have required re-implementation of SunVR functionality before development of SpaceVR could begin.

A. Sun Visualization

Solar images were downloaded using the webscrapper tool from the NASA web server. Specific Solar events such as the 2012 transit of Venus were recommended by the project clients, who teach Space Science. The images for each solar event were stored using the addressables plugin's asset tagging system. A tag was created for each of the 11 Solar events and assigned to the images. Addressables loads all the images with a specified tag on demand. This approach has benefits and downsides. Addressables allows the loading of specific images belonging to one solar event, reducing memory usage and improving performance. However, this approach could be more fine grained, it would be better if only the single image that the player is seeing was loaded instead of the entire event. Each event contains 14 days worth of images in order to capture a 180 degree rotation of the Sun. As SDO takes an image about every 15 minutes, across multiple wavelengths, this corresponds to about 4000 to 6000 images of the Sun per event. The high quantity of images causes SpaceVR to use around 20GB of RAM when an event is loaded. This implementation will not run standalone on the Meta Quest 2 as it only has 6GB of RAM.

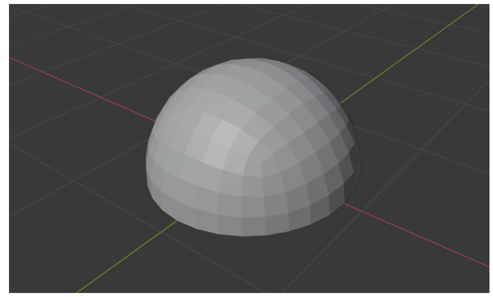


Fig. 8. The underlying shape of the virtual sun.

To show SDO images to the player within Unity a half sphere object was created and UV texture mapped within Blender. Within Unity, code was written to select the appropriate image as described in Figure 6 and instruct Unity to replace the texture on the half sphere with the new Sun image. Figure 8 shows the object and Figure 9 shows the final effect.

SDO produces images of the Sun in several wavelengths. Each wavelength highlights details in different parts of the Solar atmosphere. To allow the player to change the wavelength they are currently viewing, a 3D model of virtual goggles were created in Blender. Interaction with the goggles was enabled with the XR interaction toolkit. The player puts the goggles up to their face to change the wavelength.

B. Player Tutorial

To implement the player tutorial a Unity Scene was created and populated with game objects. A custom event object type was created in Unity. An event object was created for each event depicted in the storyboards. The list of events is shown in Table II. The custom event object was made instead of using an *off-the-shelf* quest system to facilitate code integration with the original SunVR project's code base and integrate with the functionality of XR interaction toolkit. Unity's event system was used to invoke functions on objects in the scene when events occurred. For example when glass broken event occurs, an audio source plays a sound recording of glass breaking.

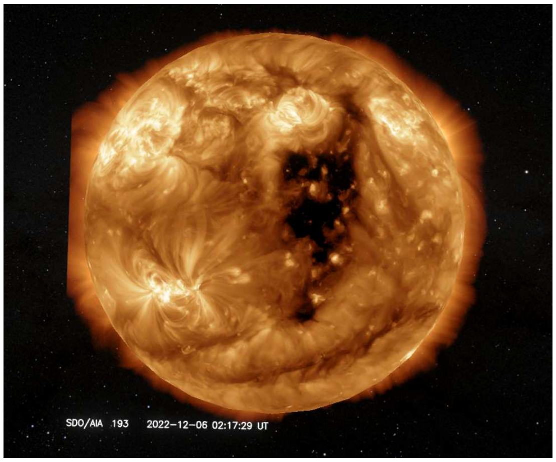


Fig. 9. An SDO image projected onto the half sphere.

TABLE II
SEQUENCE OF EVENTS IN SPACEVR TUTORIAL

Tutorial Events
Start button pressed
Glass broken
Safety goggles equipped
Activity selection button pressed

Screenshots from the tutorial are shown in Figure 10. Within the tutorial SDO images are used in the activity selection area, shown in Figure 10c to provide a preview of the following player activity.

C. Solar Flare Activity

Similar to the tutorial implementation, the Solar flare activity is implemented in a Unity Scene. Screenshots from the Solar flare activity are shown in Figure 11. Events were created for each event in the storyboard. The events are listed in Table III. The scene is populated with art assets created in Blender, which can be seen in the figures. Custom Blender models were chosen over pre-made 3D models to meet the object layout requirements specified in the storyboards. The Earth model in the background of Figure 11a is the exception, it is an off-the shelf model from Sketchfab because its layout was not specified in the plan.

The Solar flare event is depicted in Figure 12. The flare is shown to the player through a combination of: images of the solar flare from the SDO data set, an audio recording of a Solar flare captured by NASA's Cassini spacecraft that is played when the flare occurs, and a custom shader effect created with shader graph is applied to the satellite model. The shader effect is shown in Figure 12c. The shader effect is used to visually show the player how Solar flares can effect man made equipment in space.

To repair the damaged satellite the player conducts a space walk where they remove the satellite's service panel. The player then removes the damaged control board and discards it. They then return to the space station to acquire a replacement control board. The appearance of the new control board is altered to indicate it has radiation hardened capabilities. The satellite is repaired when the player inserts the new control board. After the satellite is repaired the player can continue looking at the Sun visualization from within the space station.

TABLE III
SEQUENCE OF EVENTS IN THE SOLAR FLARE ACTIVITY

Solar Flare Activity Events
Experience start
Equip goggles
Solar flare occurs
Satellite damaged
Space helmet equipped
Repair sequence start
Satellite service panel opened
Repair sequence complete

D. Locomotion

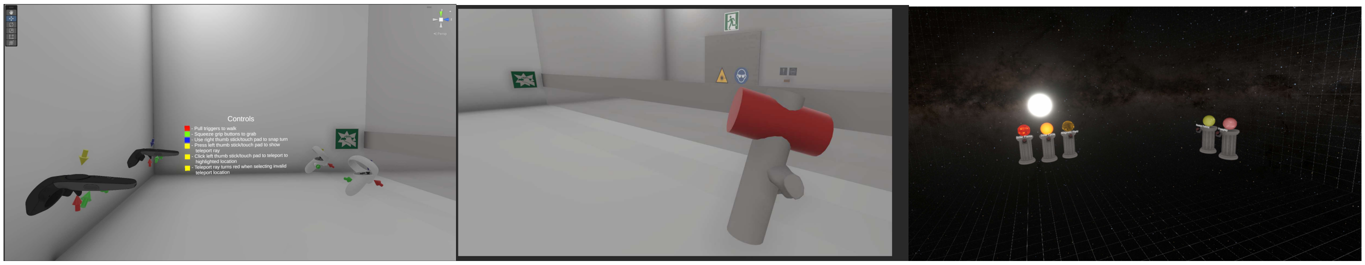
To enable player locomotion we used the XR interaction toolkit. The toolkit provides an object called the *XR Origin* which the player controls. Game scripts can control and move the *XR Origin* in response to player actions. SpaceVR uses the toolkit's ready made implementation of teleportation to avoid duplication of effort. We are not aware of any public implementation of trigger walking, so SpaceVR provides its own implementation by overriding the XR interaction toolkit's Locomotion Provider class. Initial testing of this implementation revealed that some participants prefer having the option to walk backwards. In the tutorial, the player can set if they want one of controllers to walk backwards. In SpaceVR's implementation, the player walks in the direction they are facing. The implementation lacks the original paper's option to walk in the direction the controllers are pointing. This option may have been more intuitive to use as it allows looking in various directions while walking in a straight line.

NFR 6 requirement was achieved by using an abstraction layer between the physical controller used and the game actions they cause. Unity Game Engine's input system allows multiple physical buttons to map to the same in-game action. The Actions such grabbing and teleportation were bound to both the HTC Vive controller and the Meta Quest controller.

E. Freeplay Mode

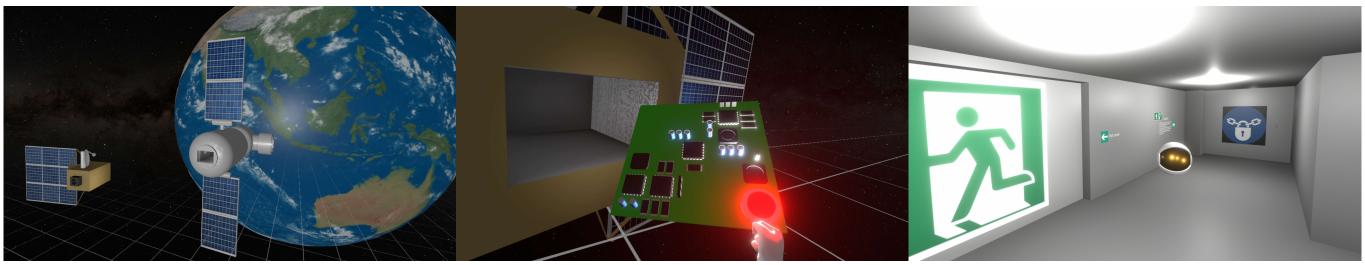
Freeplay mode is the original SunVR project implementation. It can be accessed in SpaceVR from the activity selection area depicted in Figure 10c. In freeplay mode the player can view all 11 Solar events in the dataset. They can also grab and rotate the sun. Figure 13 depicts the sun grabbing mechanic. When the Sun is rotated the angle is sent to the virtual clock to update the time. The time is updated by dividing the angle by the angular rotation of the Sun in degrees per second. The same process is performed when the player walks around the sun. The number of degrees the player has walked around the Sun is determined each update with the dot product between the Sun's forward vector and a vector that points from the Sun to the player.

Freeplay mode also has throw-able *control items* that can pause the virtual clock or make it rewind time. The control



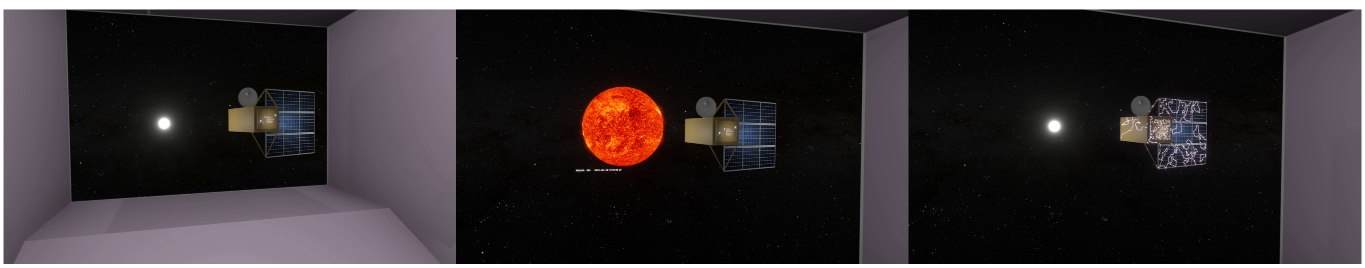
(a) The controls. (b) The glass obstacle. (c) The activity selection area.

Fig. 10. Screenshots from the player tutorial.



(a) The virtual environment. (b) The player removes faulty control board from the satellite. (c) The airlock and space helmet.

Fig. 11. Screenshots from the Solar flare activity.



(a) Player view from space station. (b) Player views images of the Sun. (c) The satellite is damaged by the flare.

Fig. 12. Additional screenshots from the player tutorial.

items are drawn towards the Sun with a force. This enables them to be thrown into around the Sun, which was noted as a fun activity during demonstrations of SpaceVR.

Fig. 13. Grabbing and rotating the Sun in freeplay mode.

V. Evaluation

A. User Test

The desktop executable artefact was evaluated using a summative user test with participants recruited on a university open day to assess the usability and user acceptance of SpaceVR. Ethics approval from Victoria University's Human Ethics Committee was obtained before testing. The ethics approval is in the report appendix.

1) Participant characteristics: Participants were a mixture of high school students and fourth year engineering students. 14 participants participated in the study, 9 were high school students and 5 were engineering students. All participants identified as male.

2) Procedure: Participants completed an initial questionnaire to screen for vulnerability to motion sickness. They then read an information sheet and signed a consent form. Before playing SpaceVR they recorded their demographics information and were informed on how to use the VR equipment. Within SpaceVR participants completed the tutorial and the solar flare level which encompassed a series of interconnected linear tasks guided by the level's storyline. This process took approximately 15 minutes. After completing SpaceVR participants filled in the surveys. Participants were compensated with a $20 supermarket voucher.

3) Study tasks: The participant tasks in the tutorial are: move to hammer, break glass obstacle, put on safety glasses, open door to activity selection area, and select Solar flare activity.

In the Solar flare activity, participants completed the following tasks: equip headphones, put on Solar filter goggles, observer solar flare, put on space suit helmet, spacewalk to damaged satellite, replace damaged circuit board in satellite.

4) Apparatus: The user study was performed using the HCI group's high performance development computer and a Meta Quest 2 VR headset. Participants were given the option of completing the experience while standing or seated positions.

5) Data Collection and Analysis: SpaceVR's evaluation used three quantitative surveys and collected written comments for qualitative feedback.

System Usability Scale. The system usability scale (SUS) is used to assess the perceived usability of a system [23]. A score of 68 indicates average usability. Scores below 68 indicates poor usability. Below 51 indicates serious usability problems. Scores above 68 indicate good usability and scores above 80.3 indicate excellent usability.

NASA Task Load Index. NASA Task Load Index (TLX) was used to measure the perceived workload of SpaceVR [24]. NASA TLX contains 6 questions: 1. How mentally demanding is SpaceVR 2. How physically demanding is SpaceVR 3. How rushed does SpaceVR feel 4. How successful did you feel at SpaceVR 5. How much effort was needed to play SpaceVR 6. How frustrating was it to play SpaceVR. In all cases lower scores are considered better.

Game Experience Questionnaire. The Game Experience Questionnaire (GEQ) was used to measure different aspects of the player's experience while playing SpaceVR [25]. GEQ has 3 components. We used the core module and post experience module. The core module measures the player's feeling of immersion, flow and competence. It measures if the player experienced a positive or negative affect and how annoyed they felt while playing. It asks how challenging the player thought the experience was. The post experience module measures how the player felt *after* completing the experience including if they thought it was a positive or negative experience, if they felt tired, and how easy it was to *'return to reality'* after completing the experience.

B. Results

1) Quantitative Feedback:

System Usability Scale. The SUS scores are shown in Figure 14. The vertical bar shows where the score of 68 is, which is considered the cut off for acceptable usability. The mean score for both high school and non high school participants was 69, just above the cut off. The mean score doesn't tell the full story because the extremities of the scores are far apart indicating the usability of SpaceVR is currently mixed.

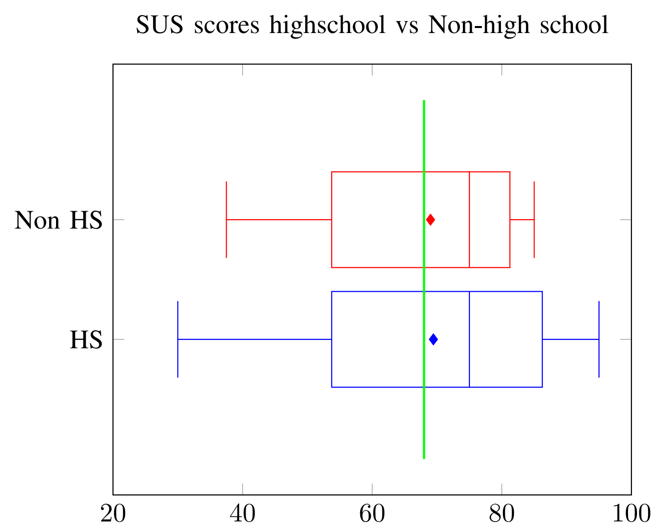


Fig. 14. SUS scores for high school participants and non-high school participants.

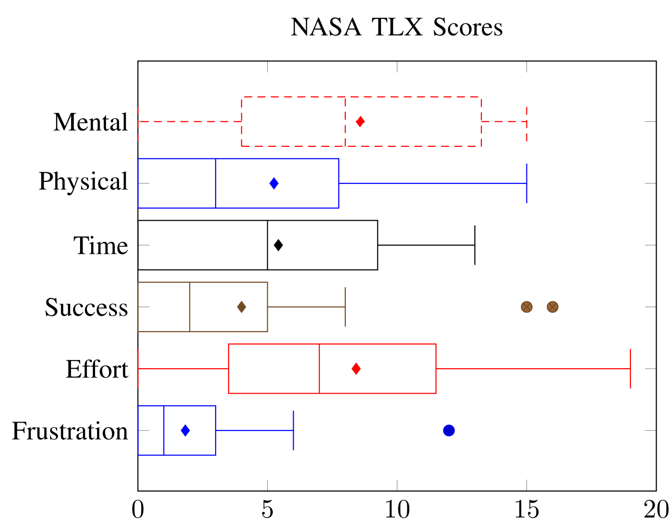


Fig. 15. NASA TLX Scores.

NASA Task Load Index. The TLX scores are shown in Figure 15. Frustration scores were low among the participants. The participants experienced a wide range of perceived effort required to play SpaceVR further hinting at usability issues in the experience. Most participants indicate that they felt they were successful at playing SpaceVR. The time scores indicate most participants thought SpaceVR was well paced. Most participants indicated SpaceVR required little physical effort to complete. The mental demand scores indicate SpaceVR required middle of the range mental effort to complete.

Game Experience Questionnaire. The core GEQ questionnaire results are shown in Figure 16. The scores are

TABLE IV
GEQ SCORES FOR ENGAGEMENT QUESTIONS

Question	Mean	Standard Deviation
Q3	2.66	1.21
Q19	2.83	1.35

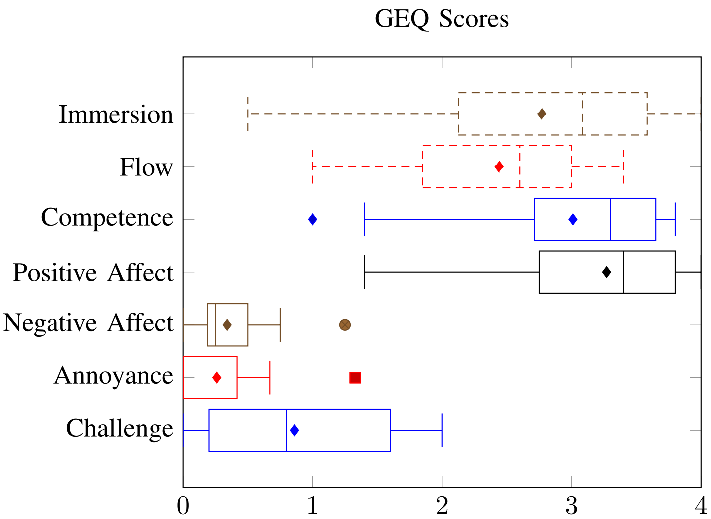


Fig. 16. GEQ scores.

generally positive with the lower quartile being part the mid point for immersion, competence, and positive affect. The presence of outliers indicate that SpaceVR did not appeal to all participants, this would likely be true for the general population, some people just won't enjoy the experience. The post experience component of GEQ is shown in Figure 17. The negative experience responses are closely concentrated around 0.17 indicating that none of the participants viewed SpaceVR as a negative experience, even though some of them disliked it. This is reinforced by the wide range of scores in the positive experience section. The returning to reality scores are concentrated below the midpoint which suggests most participants were able to exit the experience without issue. GEQ includes two individual questions that can proxy for how engaged the player felt: *19. "I felt I could explore things"* and *3. "I was interested in the game's story"*. The scores for these questions are shown in Table IV. The mean for each question is above the mid point of 2.

2) Observations: The time taken to complete SpaceVR varied significantly by the player's prior experience level. Although not explicitly recorded, we observed participants that self identified as being familiar with virtual reality as being much faster at completing the experience and requiring less assistance from the experiment facilitator.

One participant unintentionally stumbled upon several bugs in the experience, which they perceived as a positive experience, as they got to see how a software application can unravel under testing.

Some participants requested to play the freeplay mode after completing the main narrative. We observed that participants universally enjoyed the freeplay experience as they could physically interact with the sun and throw physics objects around the environment. Trying to throw a physics object into orbit around the sun was observed as an enjoyable activity.

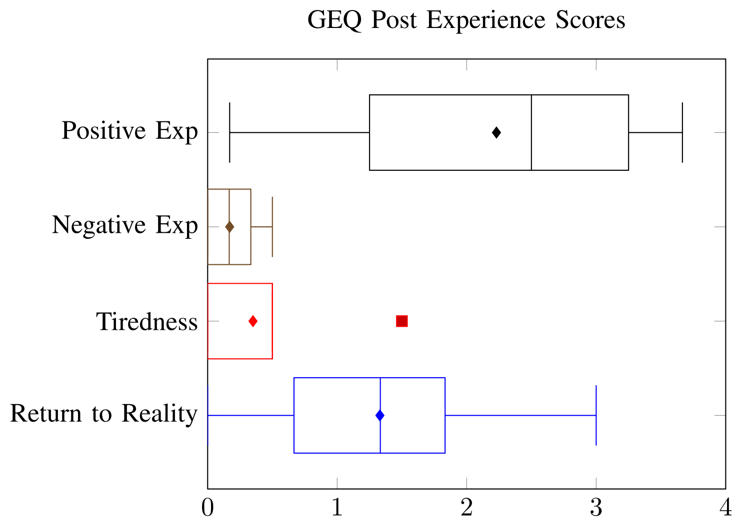


Fig. 17. Post experience GEQ scores.

Steam's performance monitor reports the framerate of the application. SpaceVR achieves NFR 5 as its framerate was recorded to be satisfactory at 100 FPS on the HCI group's development computer.

3) Qualitative Feedback: All high school participants except for one expressed that the experience was positive.

> "The game was very well built and I loved how responsive the controls are compared to other VR games I have played." (PID5)

Some participants were highly immersed in the experience.

> "It was a good experience and I was able to connect with the game. I felt as if I was in another world ... I highly recommend this, as it was a great experience." (PID6)

One participant thought the experience was novel compared to other STEM experiences they had encountered.

> "It was a fun experience, easy to use, looked great, and was different compared to other technological experiences" (PID 7)

Constructive criticism from the highschool participants centered around the aesthetics of the experience and the player activity.

> "I would suggest adding more texturing and beveling to models to make it more aesthetically pleasing." (PID 5)

One participant did not enjoy SpaceVR, expressing that the player task would be better if it had no backtracking and a focus on something other than Solar flares and satellites.

> "[SpaceVR] needs polish and maybe refocusing on the interesting parts of space travel. It felt janky to use with the tasks not well conveyed to the player ... [SpaceVR needs] more things to do, with less fetch quest energy. Game needs more effort in being either: fun, interesting, or refined." (PID 11)

One of the non high school participants believed that they didn't learn anything from playing SpaceVR.

> "I think adding more educational aspects would be beneficial without detracting from the entertainment." (PID 12)

C. Discussion

As mentioned in the design section, the plan for the Solar flare activity was to get something up and running quickly to get user feedback. The activity has achieved this goal as we collected feedback on usability and the experiences of the participants.

Participant 11's comment that the experience should be more refined, interesting, or fun is important and its worth discussing how *fun* and *interest* can be increased in SpaceVR. Erik Champion and Simon McCallum offered insights into the challenges that educational games face in their Game Design Prototyping Workshop [26] that we can use to help understand where SpaceVR might improve. When a game has balance, there are systems to learn and master. Currently the only system the player can master in SpaceVR is the movement. Additional systems should be considered in future player activities, such as the object throwing in the freeplay mode. Having no challenge can also lower the engagement. There should be obstacles to impede the players progress that are overcome. SpaceVR's obstacles are currently a glass wall obstacle that is smashed with a hammer and various doors and hatches that can be opened. More interesting challenges to player progression should be considered, especially around the time in the experience when the Solar flare occurs. SpaceVR also has a lack of game mechanics that reward or punish the player. Narrative progression, like the Solar flare activity's advancing story, can be a form of positive feedback but is rarely the primary mechanic. We believe fun, refinement, and interest should be key performance metrics used when assessing future player activities.

The user feedback on the graphics of the experience are interesting because they suggest that SpaceVR could be improved further simply by refining the visual appearance of the game. An interesting finding is the bimodal distribution of usability scores. We believe it is unlikely that a 'one size fits all' control scheme exists for VR, so it may be better to implement more locomotion options and allow the player to choose the options they want. A positive finding is that most players felt the experience had a positive affect on them as the mean score for positive affect was 3.27 out of 4.

The outer space environment was immersive for most participants, which can lead to improved engagement. 10 out of 14 participants reported that they felt they could 'explore things' in the activity which is another indicator that the experience was engaging.

Another finding from the qualitative feedback is that some participants were unsatisfied with 'on-demand' pop up textual instructions. Persistent on screen instructions may have been better. Another approach that could be explored is using environmental story telling to eliminate the need for text instructions.

The last finding is that FR 2, the explanation of the Solar flare, is not being met in the current artefact. One participant commented that they did not feel they learned anything from the experience. While teaching Space Science concepts was not a goal of the project, participants should at least feel they are getting a taste of what the Space Science field has to offer.

D. Limitations

The study had several limitations worth discussing. First, a sample size of 14 is small therefore conclusions drawn from participant feedback, such as the usability of the application, may not reflect the general population. Second, all of the participants identified as male. This means insights from the female perspective have not been captured. Although several females expressed interest in study participating on the university open day, none of them wanted to wait in the queue and ended up exploring other activities on the open day. The study contained no baseline comparison against SunVR or Helioviewer. There was a missed opportunity to A/B test the freeplay mode (no narrative) against the solar flare activity (narrative) to conditionally test if adding tasks and a story resulted in a better experience. This would have helped answer the research question. Lastly, the questionnaires did not include an explicit question asking about user engagement. Participant engagement must be inferred by proxy from GEQ questions.

The produced artefact's primary limitation is high memory consumption and size. The visualization loads all Solar images for a given Solar event into memory at once even through the player only sees one image at a time. High memory consumption means the artefact currently only runs on a high performance computer that must be tethered to a headset, limiting its portability and preventing a standalone version of the application. The artefact is also notably missing planned voice commentary that would have provided explanations and context for the player.

VI. Conclusions and Future Work

SpaceVR is VR experience that incorporates NASA SDO data and narrative to create an engaging experience about Space Science targeted at high school students. A user study was performed to assess the usability and user acceptance of the experience. SpaceVR built upon the SunVR project, using Unity Game Engine, Blender, and a custom made SDO image download tool.

This project investigated how narrative and SDO data could be used to create an engaging VR Space Science experience. The produced artefact meets meets functional requirements 1, 2, 5, 6, and 7. Functional requirements 3 and 4 were not met due to time constraints. Qualitative user feedback supports the conclusion that narrative on its own is not sufficient for creating an engaging VR Space Science experience, yet despite this 64% of participants had positive experience scores above the mid point.

Despite meeting all of the non-functional requirements, which were focused on producing an easy to use experience, the mean usability score was 69, just one point higher than the minimum score for acceptable usability. User feedback indicates that NFR 2, provide alternate locomotion methods, and FR 6, communicate required actions to the player, are good opportunities for further investigation. Subsequent projects could investigate better ways to communicate the task to the player beyond a text pop up. They should also investigate if offering many locomotion methods and allowing the player to choose is better than SpaceVR's combination of teleportation and trigger walking.

There is an opportunity to expand upon this work by optimizing the memory usage of the Sun visualization. If the visualization's memory usage was reduced then SpaceVR could be deployed to the standalone headset, making it more portable and suitable to take to Space Science outreach events.

This work lays the ground work to explore more interesting VR player activities that make use of the Sun visualization. During the design stage, several possible player activities were considered before the Solar flare activity was chosen for implementation. These player activities should be revisited with an eye for game mechanics and challenges that are engaging for the player. The alternate player activities represent an opportunity to go back to the drawing board on how we explain complex Solar phenomena to the player within VR.

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