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An Educational Experience to Raise Awareness about Space Debris

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ABSTRACT Space debris represents a threat to space missions and operational satellites. Failing to control its growth might lead to the inability to use near-Earth space. However, this issue is still largely unknown to most people. In this paper, we present an educational experience in virtual reality created to raise awareness about the problem of space debris. The application exploits the entity-component-system (ECS) programming pattern to manage around 20000 orbiting objects with a high frame rate to convey a fluid experience. We preliminarily validated our application, in terms of usability as well as quality of user experience, during several events involving both a broad audience (e.g., citizens of all ages, from teenagers to elders) and an experienced audience (e.g., engineering students enrolled in the aerospace degree). The results of the evaluation were extremely positive, showing once again that virtual reality can be an effective means to engage people in captivating and interactive activities, making them experience what can only be imagined — the thousands pieces of space debris surrounding our planet.

INDEX TERMS Aerospace Engineering, Satellites, Virtual Reality, Space Debris.

I. INTRODUCTION

Several thousands of man-made objects orbit the Earth at different altitudes. The US Space Surveillance Network currently tracks more than 23000 objects, with sizes ranging from 10 cm to a football field (CelesTrak, 2019). According to the European Space Agency (ESA) there are approximately 750000 objects larger than 1 cm untraceable by current technology. Only 6% of the known orbiting objects are active while the remaining 94% of them are man-made objects in space that serve no purpose, i.e. space debris (Colombo et al., 2018).

Space debris represents a threat to space missions and operational satellites. Due to the high orbital speed, an impact with a fragment as small as 10 cm or less could result in the partial or complete loss of a mission. When there is a risk of collision with space debris, operators must assess in a timely manner whether to perform a collision avoidance maneuver. Such maneuvers require fuel that could otherwise be employed for main operations and often require a momentary suspension of service, which may be infeasible because of the mission constraints. Space debris also poses a threat to people and properties on the ground. When a large uncontrolled object re-enters the atmosphere, part of it is demised while between 10% and 40% of its original mass reaches the Earth's surface as fragments. These surviving fragments possess enough energy to severely damage what they hit and they also pollute the environment. On the other side, services from space are now fundamental to life on Earth. Therefore, to keep counting on them, the sustainable development of space activities is recommended, by limiting the creation of new debris objects and reducing the already existing ones.

There are several applications for virtual reality that let users explore our galaxy and the solar system (Blue Cow Entertainment, 2020; Microsoft Corp., 2020), visit the International Space Station (ISS) (MAGNOPUS, 2020), or be an astronaut (Muchoviento Studios, 2020) and have a space walk (Opaque Media Group, 2020). These applications mainly focus on providing visually captivating experiences rather than scientifically accurate ones. On the other hand, ESA released several freely available videos to explain key concepts of space exploration and space debris (ESA, 2017).

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However, videos lack interactivity and give no agency to users. The application we developed aims at providing an accurate scientific simulation and also interactivity, a feature often missing in existing scientific multimedia artifacts. To our knowledge, the experience we designed is the first one with the main focus on the space debris problem.

In this paper, we present an experience in virtual reality (VR) that we created to raise awareness about the problem of space debris. Our application targets both a general audience and people with background knowledge about space missions; it aims at raising people's awareness about the space debris problem. The application has been designed for head mounted displays connected to a computer (like for example, Windows Mixed Reality headsets[1]) as well as stand-alone ones (like Oculus Go and Oculus Quest[2]). The experience has a story mode, for the dissemination of information about the space debris problem, and an exploration mode, targeting a more experienced audience, that lets users take a stroll in near-Earth space. We present the results of a validation we conducted both with engineering students and a general public. Overall, the results suggest that our application can be an effective means to communicate the problem of space debris to a broad audience and may also enhance the tutoring process of orbital mechanics related topics.

The paper is organized as follows. In Section II, we introduce space debris, explain why it poses a threat to space missions, and discuss how this issue has evolved since the beginning of the Space Age. In Section III, we discuss the recent applications of virtual reality to education and the ones devoted to space exploration. In Section IV, we present the design of our application including the initial requirement specification phase, its overall structure, its main components (the narrative, the tutorial, and the exploratory section), and the technical challenges faced in the development. In Section V, we present the results of the evaluation performed with human subjects. In Section VI, we draw some conclusions and outline future research directions.

II. SPACE DEBRIS

Every day thousands of man-made objects orbit around the Earth at different altitudes. For cataloguing reasons, there exist three distinct orbital regimes: (i) a Low Earth Orbit (LEO), ranging from 300 to 2000 km of altitude; (ii) a Medium Earth Orbit (MEO), ranging from 2000 km to 36000 km; or (iii) a Geostationary Orbit (GEO), travelling at an altitude of about 36000 km. The US Space Surveillance Network's data set (CelesTrak, 2019) tracks more than 23000 of them, from 5-10 cm of size in LEO and from 0.3-1 m in GEO (Colombo et al., 2018). Only 6% of these objects are active satellites that are currently carrying out the task for which they were designed; the remaining 94% of them are inactive space debris.

Figure 1 shows the composition of orbiting objects: 59% of the objects orbiting the Earth are fragments generated by

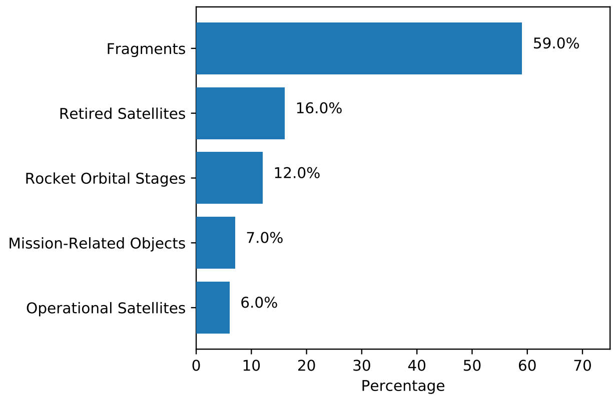

FIGURE 1. Composition of the catalogued orbiting objects.

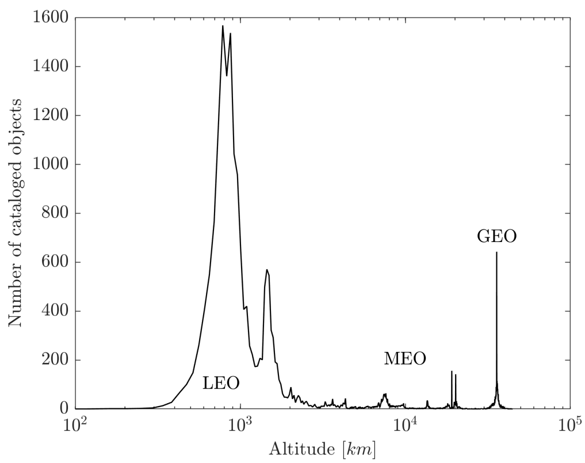

FIGURE 2. The number of the currently catalogued objects as a function of the altitude.

collisions or explosions; 16% are retired satellites; 12% are parts of rockets that were used to put the payloads in orbit; 7% are other mission related objects. The number of the operational satellites adds to a mere 6% of the total population. The different orbital regions are also unevenly populated: for instance, the portion of the LEO region between 800 and 900 km is the most crowded area (Figure 2) due to the presence of many remote sensing missions which follow a Sun-synchronous orbit to exploit the stable illumination conditions that favor observations.

A. THE THREAT OF SPACE DEBRIS

Space debris represents a threat to operational payloads. Due to the high orbital speed, an impact with a fragment as small as 10 cm or less can result in the partial or complete loss of a mission (McKnight, 2016). Accordingly, when a collision warning is received, satellite operators must assess in a timely manner whether a collision avoidance maneuver is needed. For example, on Monday 2 July 2018, ESA engineers were forced to move the CryoSat-2 satellite to a higher orbit to

[1]https://www.microsoft.com/en-us/windows/windows-mixed-reality
[2]http://www.oculus.com

avoid a piece of debris traveling at 4.1 km/s so as to save the satellite worth 140-million Euros (Witze, 2018). However, such maneuvers require fuel that could otherwise be employed for the main operations. Thus, only collisions above a certain threat probability threshold are actually avoided. Furthermore, collision avoidance maneuvers often require a momentary suspension of the ordinary service, which is often infeasible (Symonds et al., 2014). When only partial information on incoming debris is available, additional clues are collected using telescopes shortly before the impact. Fragments smaller than 1 cm could be, in theory, neutralized with shields (Crowther, 2013). However, fragments between 1 cm and 10 cm can neither be blocked by shields nor tracked; therefore, they are incredibly dangerous. In fact, McKnight et al. (2014) suggested that such small non-trackable objects might become a primary factor in the decrease of space flight safety.

B. THE HISTORY OF SPACE DEBRIS

The Space Age began with the launch of Sputnik 1 on October 4, 1957 and, over the years, the number of objects orbiting the Earth has increased dramatically. Figure 3 shows the evolution of the number of catalogued objects in space with colors representing their classes (ESA Space Debris Office, 2018, Fig. 2.1a).

Kessler and Cour-Palais (1978) were the first to postulate that collisions and explosions in orbit could lead to a cascade effect causing a dramatic increment in the number of space debris that would make near-Earth space missions too hazardous to conduct. For a long time, nations individually gathered the technical expertise to tackle the problem. However, its global nature called for the need of sharing the acquired knowledge at an international level. It was only in 1993 that the Inter-Agency Space Debris Coordination Committee (IADC) was founded and, nowadays, it is the major international technical body in the field of space debris (Letizia, 2015).

Fragmentation of large, unbroken objects is one of the major factors influencing the long-term evolution of the space debris environment (Rossi et al., 2015). The two sudden increases in Figure 3, corresponding to years 2007 and 2009, are due to two catastrophic fragmentation events. In 2007, China conducted an anti-satellite test which led to the intentional destruction of the Fengyun-1C. The 880 kg satellite split in almost 2000 fragments that increased of more than 60% the spatial density of objects at its fragmentation altitude (Pardini and Anselmo, 2007). The satellite was hit at an altitude of 863 km, where atmospheric drag, which is the only available natural sink mechanism for space debris, is not very effective. Therefore, part of the generated fragments will remain in orbit for a long time (Pardini and Anselmo., 2011). In 2009 the non-functional satellite Cosmos 2251 crashed into the operational Iridium 33 destroying it and creating more than 2000 new fragments (Pardini and Anselmo, 2014). Since the collision happened at an altitude similar to that of the Chinese missile test, the same problems in terms of the fragment orbital life apply.

III. RELATED WORK

In this section, we briefly overview the most relevant applications of virtual reality in education (Section III-A) and in space exploration, both for traditional media and virtual reality (Section III-B). Since providing a complete review on virtual reality in education is beyond the scope of this paper, we refer the interested reader to these recent surveys (Bekele et al., 2018; Freina and Ott, 2015; Fuchs, 2017; Greenwald et al., 2017; Hite et al., 2018; Mikropoulos and Natsis, 2011; Scott et al., 2017) for a discussion of earlier published works and specific areas of application.

A. VIRTUAL REALITY IN EDUCATION

In the recent years, the number of applications of virtual reality to education has dramatically grown. These applications provide ad-hoc learning experiences in several fields such as history (Liao et al., 2019), biology (Lartigue et al., 2014), language learning (Chen and Hsu, 2019; Cheng et al., 2017), architecture (Angulo and Velasco, 2013), computer science (Bujdosó et al., 2017; Grivokostopoulou et al., 2016; Parmar et al., 2016; Puttawong et al., 2017), and engineering (Abulrub et al., 2011; Cecil et al., 2013; Makarova et al., 2015). Experiments with virtual reality in these areas showed improvements in the students' learning outcomes compared to traditional classes. Such performance gains have been linked to increased levels of *presence* (Gibson, 1979), immersion, and engagement in the task at hand (Krokos et al., 2019; Ragan et al., 2010). Chen et al. (2019) also reported that, while wearing an Head-Mounted Display (HMD), students were cut off from possible sources of distractions (e.g. social media, smart phones, or surfing the web). Ip et al. (2019) and Pinto et al. (2019), on the contrary, found no learning improvements with respect to traditional classes but reported a better overall learning experience in terms of enjoyability and motivation of the students. Notably, situated learning has received great benefits from the combination with immersive technologies. In fact, virtual reality gives the possibility of exploring places that might be hardly, or even not at all, accessible (Dawley and Dede, 2014; Zhao and Klippel, 2019). Furthermore, immersive virtual environments also help students create better spatial models of their surroundings (Krokos et al., 2019; Zhao and Klippel, 2019) and grasp more clearly the 3D shapes of objects (Sharma and Chen, 2014; Shibata, 2019). As reported by Liao et al. (2019), online learning suffers from high drop-out rates because of loneliness and isolation issues due to the lack of social interactions. Contacts with co-learners provide fundamental stimuli to keep the learners engaged and motivated. Sharma and Chen (2014) developed a multi-user collaborative classroom. Instead, Liao et al. (2019) developed a VR classroom populated by virtual classmates and simulated different behaviors based on previously gathered comments made by real people on online courses. Furthermore, Bailenson et al. (2008) exploited virtual classmates, either with a good or

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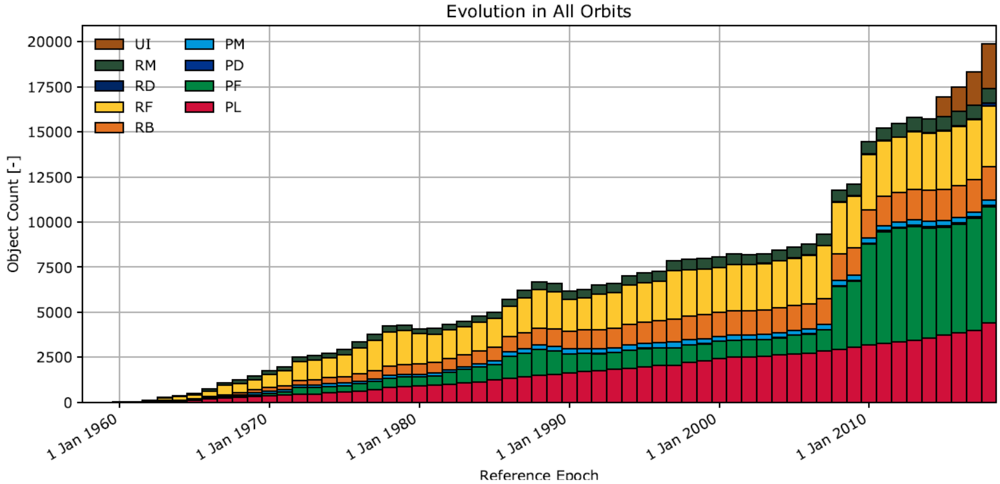

FIGURE 3. Evolution of the number of objects in geocentric orbit by object class (ESA Space Debris Office, 2018, Fig 2.1a): rocket mission related objects (RM); rocket debris (RD); rocket fragmentation debris (RF); rocket bodies (RB); payload mission related objects (PM); payload debris (PD); payload fragmentation debris (PF); unidentified objects (UI); payloads (PL).

disruptive conduct, to show that students tend to adhere to their classmates' behavior.

Virtual reality shows potential also for training purposes. It allows to practice any number of times in a safe environment tasks that might be too dangerous or too costly to reproduce in the real world. Moreover, several results show that skills gained in such simulations are transferable to real life situations (Mantovani and Castelnuovo, 2003; Ragan et al., 2010) and are retained over a longer period of time (Chittaro and Buttussi, 2015). Some existing applications provide training for firefighting (Clifford et al., 2018, 2019; Vichitvejpaisal et al., 2016), military purposes (Rashid, 2017; Taupiac et al., 2019), industrial processes (Manca et al., 2013), helping teachers deal with disruptive behaviors (Lugrin et al., 2016; Yun et al., 2019), surgery (Baheti et al., 2008; Schijven et al., 2005; Ström et al., 2006; Wu et al., 2016), safety procedures (Chittaro and Buttussi, 2015), and dealing with stressful situations (Lourdeaux et al., 2019; Stinson and Bowman, 2014).

Finally, virtual reality has a great potential to empower people by fostering their creativity (Thornhill-Miller and Dupont, 2016), helping them to overcome personal limits, like for example anxiety (Nazligul et al., 2019), or providing them with a space for self-intervention to decrease stereotype threat and increase motivation (Starr et al., 2019).

B. SPACE EXPLORATION

There are several commercial applications of virtual reality focused on space exploration (Gorman, 2020; Space, 2020) that let users explore our galaxy and the solar system (Blue Cow Entertainment, 2020; Microsoft Corp., 2020), drive a rover on Mars (Reichhardt, 2017), visit National Aeronautics and Space Administration (NASA) headquarters or the International Space Station (MAGNOPUS, 2020; Reichhardt, 2020), be an astronaut (Muchoviento Studios, 2020) and have a space walk (Opaque Media Group, 2020). SpaceVR (2020) developed zero-gravity float tanks that let users orbit the Earth using ultra high definition headsets while simulating the absence of gravity.

To our knowledge none of these applications deals with the issue of space debris. Indeed, ESA has produced several traditional videos to explain key concepts of space exploration and space debris (ESA, 2017). However, videos lack interactivity and do not give agency to users who become passive spectators. Published research includes Gao et al. (2011) who developed a desktop client server application to visualize the status of orbiting objects based on Object-Oriented Graphics Rendering Engine (OGRE). The system had severe performance issues and in its original inception, with just 500 orbiting objects, could only reach 11 frames per seconds (fps). To attain an acceptable performance of 30 fps the system was optimized by rendering points instead of actual meshes to show debris and satellites. Sagardia et al. (2015) developed a virtual reality experience, integrating a two-hands haptic device, to simulate satellite maintenance procedures for training humans. Our experience aims at providing a scientifically accurate simulation of the objects orbiting around the Earth in a real-time interactive virtual reality environment. Interactivity is of paramount importance since we don't want users to be passive spectators.

IV. THE VIRTUAL REALITY SPACE DEBRIS EXPERIENCE

Our goal was to create an educational experience to raise awareness about the problem of space debris, targeting a general audience and students (both at high school and at university level). ESA released several multimedia artifacts to explain key concepts of space exploration and debris that are freely available (ESA, 2017). Their content, however, is limited to presentations and videos that are not interactive and do not give any agency to the users.

Our research group, involving both virtual reality and aerospace engineering experts, has identified a list of requirements for the experience. First and foremost, the application had to be as much as possible scientifically accurate and had to convey the feeling of the space debris problem. It had to include a story-driven mode to narrate the story of space debris and show the various objects orbiting the Earth. It had to include an exploratory experience to let users examine the population of items orbiting the Earth, select different types of objects (e.g., payloads, fragments, rocket bodies), and orbits (e.g., LEO, MEO). Finally, it had to run smoothly both on high-end Microsoft Mixed Reality headsets, linked to a PC, and stand-alone, low-cost, headsets with limited processing power such as Oculus Go and Oculus Quest.

The experience we designed begins asking users whether they want to start in story mode, viewing the accompanying tutorial, or directly jump into exploration mode. When starting in story mode, users are presented with a series of dialogues narrating the history of space debris and showing the wide variety of objects orbiting the Earth with their trajectories. Next, the tutorial explains how to use the controller to navigate and interact with the environment. Finally, users enter the exploration mode. Experienced users can skip both the story mode and the tutorial to directly enter the exploration mode.

A. THE STORY MODE

This part of the experience illustrates the space debris problem to an audience with no background knowledge in the field and also provides general information about the satellites and debris orbiting the Earth. At first, the user is placed in space, facing the Earth, and only ISS is visible. Informative panels appear right in front of the user (Figure 4), one at a time; they cannot be dismissed before 1.5 seconds to limit the possibility of quickly skipping through. Satellites and debris are added progressively as the narration advances, to avoid distracting the user from reading the panels. Users cannot change their position, which is automatically adjusted during the narration to provide a better perspective of the objects orbiting at different distances from the Earth; only head rotation is allowed.

B. TUTORIAL

The tutorial teaches users how to use the input devices to access the multiple functionalities offered by the experience. During the tutorial users are shown how to interact with the menu to perform the available actions (e.g., to activate or deactivate objects, trajectories, etc.). Then, they are introduced to the navigation systems that allow users (i) to move on concentric orbits at varying distances from the Earth and (ii) to teleport to specific landmarks, marked by pink icosahedrons (Figure 5).

C. THE EXPLORATION MODE

This part of the experience lets users wander in the near-Earth space using teleportation between navigation landmarks, positioned on a sphere surrounding Earth (represented as pink icosahedrons, Figure 5). Landmarks are uniformly distributed around the Earth at a distance that depends on the current user position: they are closer to Earth when the user explores lower orbits; they are farther away when the user explores outer orbits.

Teleportation is a common way to implement movement in virtual reality environments that limits the risk of users getting motion sickness (Boletsis, 2017). In our application, we introduced teleportation to avoid this issue and, most importantly, to constrain the navigation of users who, during our early tests with free navigation, were easily lost because of the absence of reference points in space and were often unable to reach the viewpoint they wanted.

Users can enable and disable specific types of space objects from the view (e.g., rocket bodies, debris, active satellites) using a menu positioned on the controller. They can highlight different satellites types (showing the active in green and the defunct ones in red) or change the scale of all the orbiting objects. We included three different scales: one provides a realistic sizing of satellites and debris with respect to the size of the Earth. However, since orbiting objects usually range from 30 cm to 4-5 m in size, they are orders of magnitude smaller compared to the planet's 6,378 km radius and thus very difficult to spot. Accordingly, we introduced two additional scales which, although not scientifically accurate, make satellites and debris more visible, especially from afar. This approach is coherent with the approach taken in existing dissemination material of the European Space Agency (ESA, 2017). Users can also highlight the trajectories of satellites on different orbits (LEO, MEO, GEO, GPS). Figure 6 shows the MEO satellites' trajectories as an example.

D. THE SYSTEM ARCHITECTURE

The experience has been developed using the Unity[3] engine and supports both high-end Windows Mixed Reality headsets, which need a connected PC, and stand-alone Oculus Go and Oculus Quest headsets, which do not need to be tethered to a PC but have limited computational power. One of the major challenges we faced in the development was managing around 20000 orbiting objects, whose positions had to be updated at least at 90 fps (frames per seconds) to avoid simulator sickness in users. Unfortunately, the traditional object-oriented pattern (the current standard in all game engines) immediately proved to be unfit and led to poor performance (15-20 fps), even on high-end computers (e.g. a computer using an 8th generation Intel i7 with 16 Gb of memory, and NVidia GeForce GTX 1080 card). Accordingly, we decided to develop the application using the recently introduced, and still experimental, Unity Entity Component System (ECS). This enforces a data-driven approach to programming and separates data and logic using three fundamental concepts: entities, components, and systems. Entities are identifiers used to navigate a collection of components. Components

[3]http://www.unity.com

FIGURE 4. Informative panels appear right in front of the user while satellites and debris are added progressively following the narration.

are data wrappers and do not contain any logic to manage such data. Systems are where all the logic is placed and filter entities based on the components they need to carry out their task. Since each system performs the same calculations on all the suitable entities in a Single Instruction Multiple Data (SIMD) fashion, its work can be parallelised and run exploiting all the cores of today's processors, or vectorised and processed on GPUs. The order of execution of different systems is fixed and is determined by building a dependency graph that takes into account their read-write accesses to particular components in order to avoid race conditions. Therefore, each system should be responsible for a very specific task, to decrease dependencies and allow maximum parallelisation.

Unity's Entity Component System employs a subset of C#, called High-Performance C# (HPC#)[4]. The absence of references types allows entities to be tightly packed in memory. They are stored in portions called chunks, each chunk containing entities with the same set of components. Since systems operate on all chunks containing entities satisfying their filters' requirements, this predictable memory layout allows to exploit optimisations like prefetching for further performance improvements.

Figure 7 shows the components layout of each entity. *Position*, *Rotation*, and *Scale* are Unity's default components for positioning and rendering an entity in the 3D space. The *CategoryComponent* allows to differentiate objects belonging to different categories (e.g. rocket bodies, debris, LEO satellites, GPS satellites, etc.) so that they can be selectively manipulated (e.g. to deactivate only a certain type). *DoublePosition* and *DoubleVelocity* are needed to store position and velocity of each entity with a higher precision than that available in Unity's *Position* component. Such high precision was required to perform a scientifically accurate simulation of the evolution of the objects positions in time. Active satellites are controlled from Earth and they are rotated to face towards it. On the other hand, space debris are only subject to inertia and, therefore, tend to keep spinning in the same direction. We modelled this behaviour by assigning to each entity either a *LookAt* component, which identifies controlled satellites, or a *RotationData* component, which stores a random initial axis around which the debris will rotate. The *Size* component influences the *Scale* to take into account the object's dimension in combination with the current scale settings.

Figure 8 shows our systems architecture. The so-called *TransformSystem* is Unity's default system for positioning objects in the 3D space before rendering them. The application's core is the *MovementSystem* which, at each frame, communicates with a C++ DLL to calculate the next position for all the entities. The *RotationSystem* makes uncontrolled space debris spin. It can run in parallel with the *MovementSystem* since the rotation to be applied is the same regardless of the object's position. On the other hand, the *PointTowardsEarthSystem* needs the updated position to correctly calculate the direction each satellite should be facing.

[4]https://blogs.unity3d.com/2019/02/26/on-dots-c-c/

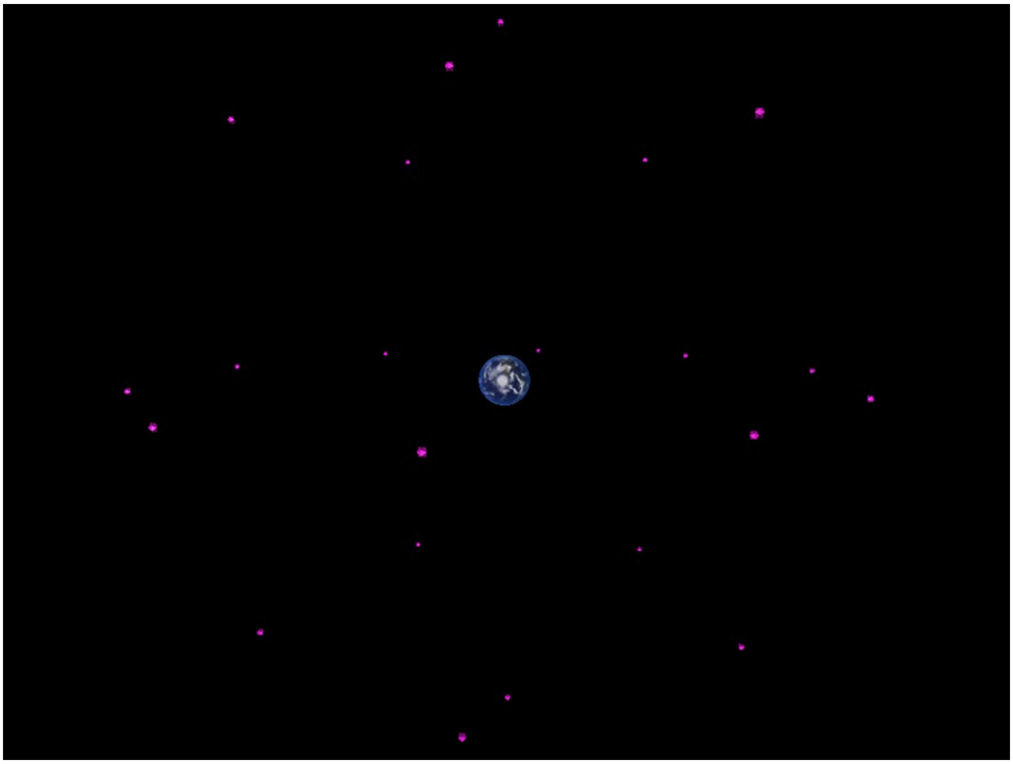

FIGURE 5. The navigation landmarks, represented as pink icosahedrons, surround the Earth at a distance that is adapted based on the distance of the user from the Earth.

The *ChangeRenderingSystem* and *ChangeScaleSystem* are independent from the other systems and can be completely parallelised, as long as they execute before the *Transform-System*. The former allows to activate or deactivate a certain category of objects. The latter updates the *Scale* component based on the *Size* component and the current scale settings. The adoption of the Unity ECS paradigm made it possible to manage all the thousands of orbiting objects smoothly even on low-cost Oculus Go visors.

The application is designed to run either as a stand-alone application, which performs both the simulation and the visualization of the data, or as a client-server application, with a remote server running the scientific simulation that is displayed on the visor also in charge of interacting with the user. The former has been designed for headsets, that have enough computational power for running the simulation and rendering the scene. The latter has been designed to allow accurate scientific simulation on low-end stand-alone headset and to support a multi-user mode (planned as a future development) that will let more people share the same simulation.

V. EXPERIMENTAL RESULTS

In this section, we report the results of the preliminary evaluation we performed during several events, including engineering students and people attending a national scientific dissemination event.

A. EARLY PROTOTYPE EVALUATION

We performed an evaluation of an early prototype during a national scientific dissemination event. The prototype envisioned users as astronauts who began their experience in the control room of a space station, with terminals displaying information about space debris. Next, they would head toward a “launch" door leading them to the outer space where they could begin their exploration of space debris surrounding the Earth. No formal experience evaluation questionnaire was administered and our feedback resides only in their reactions to the experience that were overall very positive. We noted however a few problems. The space station environment was too rich and distracting for people who were not accustomed to virtual reality. Accordingly, people tended to pay no attention to the screens narrating the history of space debris and later had problems in locating the “launch" door leading to the next stage of the experience. The evaluation of the early prototype led to the current highly simplified structure of the experience in which (i) everything happens in one environment, the space surrounding the Earth; (ii) the tutorial and the story of space debris are presented through dialogs while the user is facing the earth; so that (iii) there is no cognitive gap between the three phases of the experience: story, tutorial, and exploration (Section IV).

B. EVALUATION WITH A SELECTED AUDIENCE

As a next step, the updated version of the application was presented during an event for journalists, start up companies,

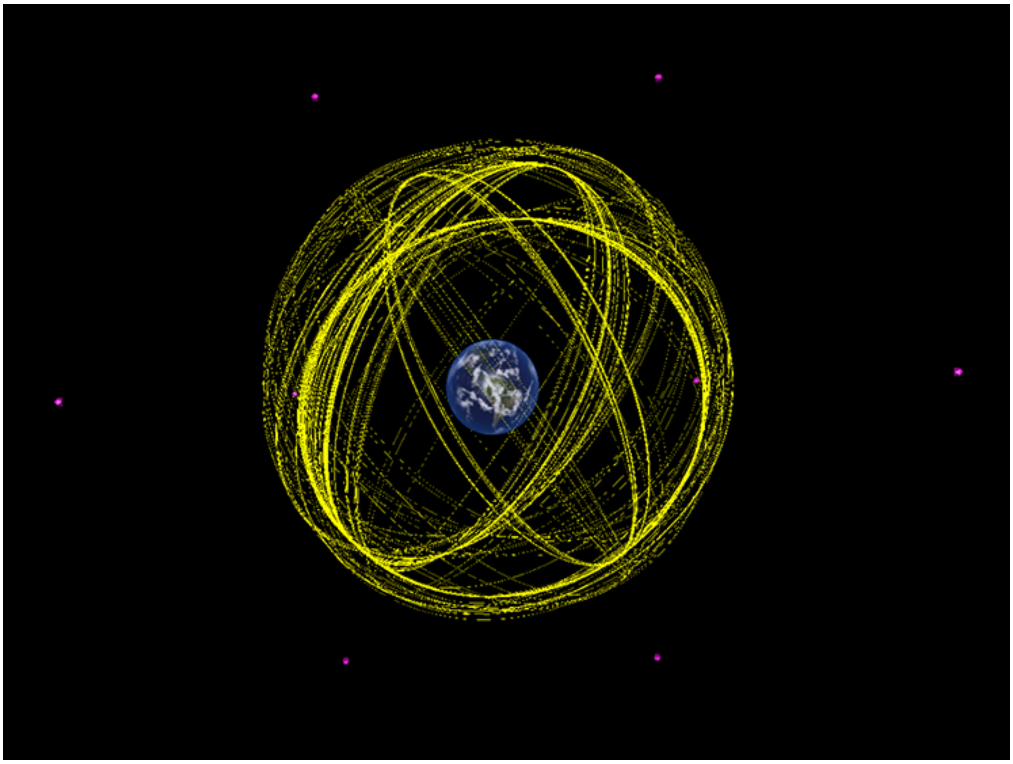

FIGURE 6. The user can highlight the trajectories of satellites on different orbits. In this case, the trajectories of Medium Earth Orbit (MEO) satellites are highlighted while all the orbiting objects are disabled.

and people from our ministry of economic development. Also in this case, no formal questionnaire was administered to the attendees and we only took into account the users' reactions to the experience and the discussions before and after the experience. Overall, we received very positive feedback. Visitors were more accustomed to virtual reality and thus less fascinated by the media with respect to the ones visiting a national scientific dissemination event. They were also focused on the scientific implication of the experience and were genuinely surprised to discover space debris to be such a threat for space missions, a fulfillment to the main purpose of the application.

C. FINAL EVALUATION

The final evaluation involved: (i) people attending our university 2019 open day event, (ii) people attending the 2019 edition of the national researcher's night, and (iii) engineering students. The evaluation involved 91 participants (22 females), 10% of them had already tried virtual reality at least once. At first, subjects received a short introduction to the experience and its scientific merit. Next, they would wear the headset. Then, once assured that there was no initial discomfort with it, they would start the experience in story mode and then move to the exploration mode (Section IV). The experience lasted around 15 minutes and, at the end, users were asked to complete an anonymous form to evaluate their overall experience. The questionnaire was adapted from the MEC Spatial Presence Questionnaire (Vorderer et al., 2004) and the IBM Usability Questionnaire (Lewis, 1995). It comprised the questions reported in Table 2. Answers ranging from 1 to 5 followed a Likert scale (Likert, 1932); for this type of answers we report the average score and the standard deviation. Questions Q3-Q11 focused on the comfort of the experience and the usability of user interface and environment. Q12-Q19 focused on the educational value of the experience and Q20-21 on the overall engagement. To evaluate whether our application caused any discomfort, we also included the sixteen questions from the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). This was designed to assess the inducement of symptoms related to simulator sickness using a four values Likert scale from 0 to 3 measuring the symptom strength (0 meaning non-existing). Table 1 reports the sixteen symptoms in SSQ (Kennedy et al., 1993) that are used to compute three scores for three symptom clusters labeled Nausea (N), Oculomotor (O), and Disorientation (D) and an overall total severity score (TS), as

$$\begin{aligned} N &= [1] \times 9.54 \\ O &= [2] \times 7.58 \\ D &= [3] \times 13.92 \\ TS &= [1] + [2] + [3] \times 3.74 \end{aligned}$$

where [1], [2], and [3] represent the sum of the answers for the symptoms selected in the corresponding columns (Table 1) while the weights used to compute N, O, D and TS were derived using factor analysis (Kennedy et al., 1993).

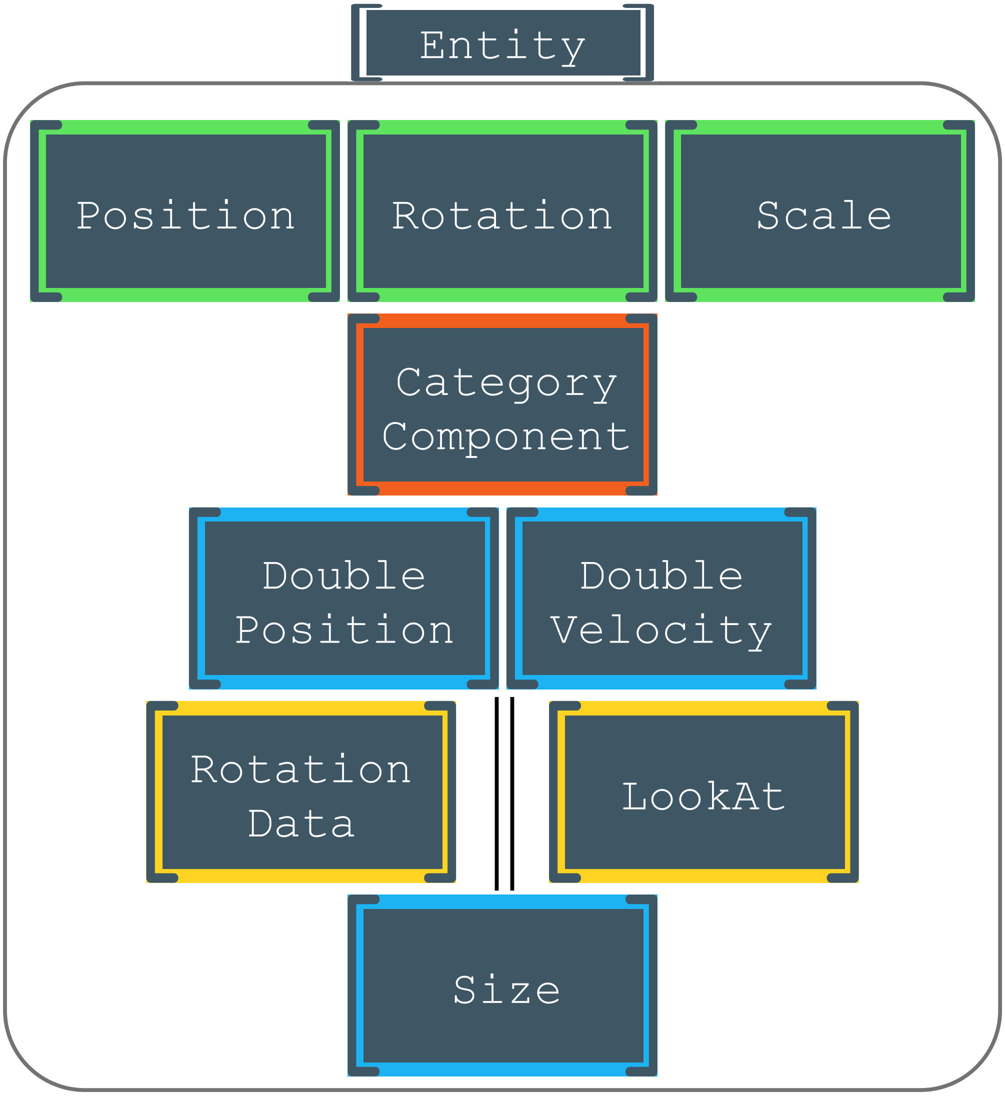

FIGURE 7. The configuration of components in our application's entities.

The authors also provided reference values ($\mu \pm \sigma$), derived from a calibration sample of 1100+ subjects, for the evaluation of existing systems: 7.7 ± 15.0 for N; 10.6 ± 15.0 for O; 6.4 ± 15.0 for D; 9.8 ± 15.0 for TS. Note that, there are other questionnaires for assessing cybersickness that are all more or less derived from SSQ, like VRSQ (Kim et al., 2018). However, the analysis of Sevinc and Berkman (2020) shows that although the alternative questionnaires are simpler and represent viable alternatives to SSQ, they have usually been evaluated on very small numbers of subjects (e.g., 24 subjects for VRSQ) and they are also highly correlated to SSQ (Sevinc and Berkman, 2020). In addition, Kennedy et al. (1993) are the only ones providing reference values for all the scores to evaluate an existing system.

TABLE 1. Symptoms in SSQ.

SSQ Items	Nausea [1]	Oculomotor [2]	Disorientation [3]
General discomfort	o	o	
Fatigue		o	
Headache		o	
Eyestrain		o	
Difficulty focusing		o	o
Increased Salivation	o		
Sweating	o		
Nausea	o		o
Difficulty concentrating	o	o	
Fullness of head			o
Blurred vision		o	o
Dizzyness (eyes open)			o
Dizzyness (eyes closed)			o
Vertigo			o
Stomach awarness	o		
Burping	o		

a: ***Comfort and Usability.***

The participants did not report any major discomfort as also confirmed by the answers to the simulation sickness

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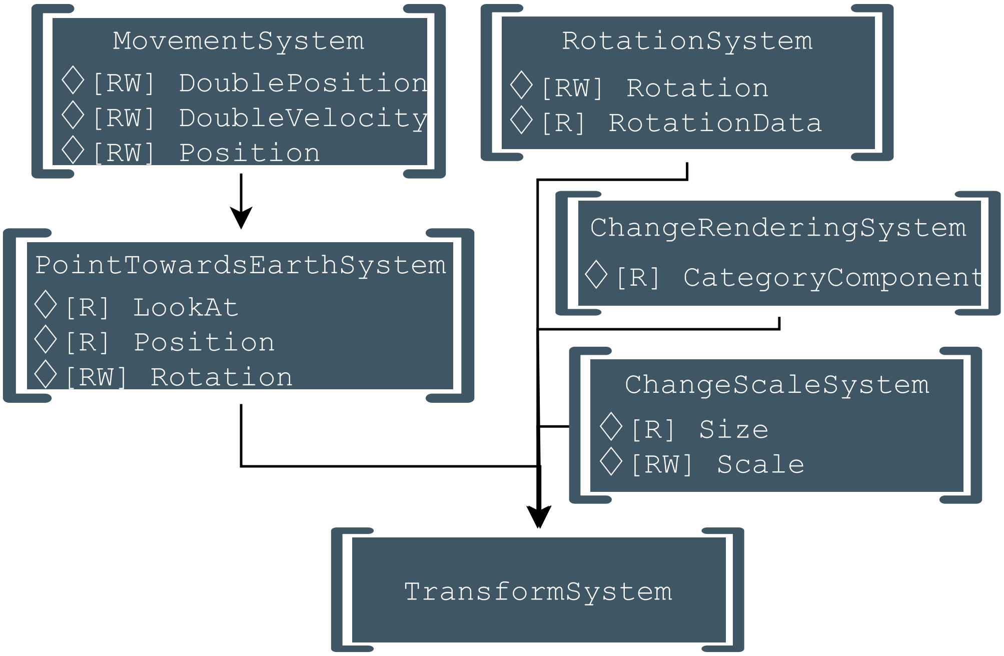

FIGURE 8. The system architecture of our application.

questionnaire. Only a couple of subjects didn't manage to get fully comfortable with the experience, while 9.9% of them reported growing uncomfortable after some time. The remainder either always felt comfortable (52.7%) or got accustomed after some exposure (35.2%) (Figure 9b). Further investigation suggested that such an initial discomfort could be due to the lack of familiarity with virtual reality. Overall, the subjects deemed the experience to be comfortable (Q5 4.36±0.71, Figure 9c).

Most of the subjects were satisfied with the usability of the experience and did not report any problem with acting in the environment (Q7 4.15±0.80, Q8 4.31±0.74, Q9 4.06±0.87, Q10 4.41±0.61, Figure 9d-g). However, people with less experience using controllers reported some trouble in accessing the menu functionalities, mainly due to the difficulty of remembering the buttons to use (Q3 18.7% False, Figure 9a). Two subjects also reported difficulties in reading the labels of the menu. Reading text is currently an issue with stand-alone virtual reality headsets which tend to have poor display resolutions. Accordingly, another subject suggested to employ visors with higher screen resolution.

b: ***Educational Value.***

Overall, the subjects did not have problems in understanding the tutorial (Q12 4.48±0.78), the informative panels (Q13 4.46±0.76), the role of the orbiting objects (Q14 4.41±0.76), the trajectories of the satellites (Q15 4.49±0.64), and the experience as a whole (Q16 4.38±0.79 Figure 10a-e). They also deemed virtual reality experiences of this kind to be an enhancement to traditional lectures they would appreciate (Q18 4.36±0.79, Q19 4.58±0.73, Figure 10f-g).

c: ***Engagement and Suggestions.***

Overall, the experience was considered engaging by the vast majority of the subjects (Q20 4.65±0.58, Figure 10h). In the final open question Q21 we received several suggestions. One subject asked for dimmer colors which we plan to introduce as a special visualization mode together with a colorblindness mode for accessibility. Other people suggested adding information about the navigation status to the display (e.g., the position from the Earth) or physical forces (e.g., the gravitational field). A more experienced student suggested to include a free navigation mode, which we did not include since our preliminary evaluations showed that it dramatically decreases usability for most people. One subject suggested to give the possibility to have a tour around Earth (like a movie) to provide a view from different viewpoints and orbits — which we do not plan to include for the motion sickness that such an animation would cause to users. It was also suggested to add an audio version of the tutorial, which we plan to include as an option in the final deployment on the stores.

d: ***Simulation Sickness.***

Figure 11 reports the results of the questionnaires for all the sixteen symptoms of SSQ. Following the procedure delineated in (Kennedy et al., 1993), for each subject, we computed the four SSQ scores, then we computed the mean and standard deviation of the four scores over all the subjects obtaining 11.01 ± 8.24 for N, 27.40 ± 26.68 for O, 25.70 ± 24.93 for D, 11.67 ± 10.43 for TS. Although our values are slightly higher than the reference values provided by Kennedy et al. (1993), the t-test shows that the differences are not statistically significant with a p-value of 0.43 for N, 0.92 for O, 0.27 for D, and 0.77 for TS suggesting that our application has basically no relevant simulation sickness issue. We also did not note any difference when analyzing the male and female populations separately.

VI. CONCLUSIONS

We presented a virtual reality experience to raise awareness of space debris in the general public and in people with some background knowledge about space missions (such as aerospace engineering students). The experience runs on high-end head mounted displays, like the Microsoft Mixed Reality headsets, as well as on the stand-alone and low-cost Oculus Go and Oculus Quest. We exploited the Entity Component System design pattern to tackle the main technical challenge, that is, to manage around 20000 orbiting objects with a high frame rate and limited computing resources. The experience has a story mode, for the dissemination of information on space debris to a general public, and an exploration mode, that allows an educational stroll in near-Earth space. We evaluated our application with people attending the open day at our university, one national scientific dissemination event, and engineering students. Each person had 15 minutes to try the experience and, at the end, was asked to fill in a questionnaire. Overall, the experience was positively evaluated by the large majority of the subjects who considered it engaging and informative, confirming once again what already shown in the literature: virtual reality can be an effective mean to involve people in captivating and interactive activities. Future research directions include the support to new platforms, the publication in online stores, and the introduction of multi-user support to let people share the same experience in real-time — a feature that could be very helpful for teaching to a class. Education-wise, we plan to perform extensive testing, both at high-school level and university level, to investigate the educational impact of the experience.

REFERENCES

Abulrub AH, Attridge A, Williams M (2011) Virtual reality in engineering education: The future of creative learning. International Journal of Emerging Technologies in Learning (iJET) 6(4):4–11, , URL https://online-journals.org/index.php/i-jet/article/view/1766

Angulo A, Velasco G (2013) Immersive simulation of architectural spatial experiences. In: XVII Conference of the Iberoamerican Society of Digital Graphics - SIGraDi: Knowledge-based Design, pp 495–499,

Baheti A, Seshadri S, Kumar A, Srimathveeravalli G, Kesavadas T, Guru K (2008) Ross: Virtual reality robotic surgical simulator for the da vinci surgical system. In: 2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp 479–480,

Bailenson J, Yee N, Blascovich J, Beall A, Lundblad N, Jin M (2008) The use of immersive virtual reality in the learning sciences: Digital transformations of teachers, students, and social context. Journal of the Learning Sciences 17:102–141,

Bekele MK, Pierdicca R, Frontoni E, Malinverni ES, Gain J (2018) A survey of augmented, virtual, and mixed reality for cultural heritage. J Comput Cult Herit 11(2):7:1–7:36, , URL http://doi.acm.org/10.1145/3145534

Blue Cow Entertainment (2020) VR Space. URL https://play.google.com/store/apps/details?id=com.bce.VR, last visited in February 2020

Boletsis C (2017) The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. Multimodal Technologies and Interaction 1(4), , URL http://www.mdpi.com/2414-4088/1/4/24

Bujdosó G, Novac OC, Szimkovics T (2017) Developing cognitive processes for improving inventive thinking in system development using a collaborative virtual reality system. In: 2017 8th IEEE International Conference on Cognitive Infocommunications (CogInfoCom), pp 000079–000084,

Cecil J, Ramanathan P, Mwavita M (2013) Virtual learning environments in engineering and stem education. In: 2013 IEEE Frontiers in Education Conference (FIE), pp 502–507,

CelesTrak (2019) NORAD two-line element sets current data. URL https://www.celestrak.com/NORAD/elements/, the Center for Space Standards & Innovation

Chen Y, Hsu C, Chung C, Wang Y, Babu SV (2019) ivrnote: Design, creation and evaluation of an interactive note-taking interface for study and reflection in vr learning environments. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 172–180,

Chen YL, Hsu CC (2019) Student self-efficacy in learning english in a wearable virtual reality environment. In: Graziano K (ed) Proceedings of Society for Information Technology & Teacher Education International Conference 2019, Association for the Advancement of Computing in Education (AACE), Las Vegas, NV, United States, pp 1324–1327, URL https://www.learntechlib.org/p/207816

Cheng A, Yang L, Andersen E (2017) Teaching language and culture with a virtual reality game. In: Mark G, Fussell SR, Lampe C, m c schraefel, Hourcade JP, Appert C, Wigdor D (eds) Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, Denver, CO, USA, May 06-11, 2017, ACM, pp 541–549, , URL https://doi.org/10.1145/3025453.3025857

Chittaro L, Buttussi F (2015) Assessing knowledge retention of an immersive serious game vs. a traditional education method in aviation safety. Visualization and Computer Graphics, IEEE Transactions on 21:529–538,

Clifford RMS, Hoermann S, Marcadet N, Oliver H, Billinghurst M, Lindeman RW (2018) Evaluating the effects of realistic communication disruptions in vr training for aerial firefighting. In: 2018 10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games), pp 1–8,

Clifford RMS, Jung S, Hoermann S, Billinghurst M, Lindeman RW (2019) Creating a stressful decision making environment for aerial firefighter training in virtual reality. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 181–189,

Colombo C, Letizia F, Trisolini M, Lewis H (2018) Space debris: Risk and mitigation. In: Wilman RJ, Newman CJ (eds) Frontiers of Space Risk: Natural Cosmic Hazards & Societal Challenges, CRC Press

Crowther R (2013) Space debris: mitigation and remediation. Clean Space Workshop

Dawley L, Dede C (2014) Situated Learning in Virtual Worlds and Immersive Simulations, Springer New York, New York, NY, pp 723–734. , URL https://doi.org/10.1007/978-1-4614-3185-5_58

ESA (2017) Space Debris 2017 - A Journey to Earth. URL https://www.esa.int/spaceinvideos/Videos/2017/04/Space_debris_2017_-_a_journey_to_Earth, last visited in February 2020

ESA Space Debris Office (2018) ESA's Annual Space Environment Report. Tech. rep., European Space Agency, URL https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

Freina L, Ott M (2015) A literature review on immersive virtual reality in education: State of the art and perspectives. In: ROCEANU I, MOLDOVEANU F, TRAUSAN-MATU S, BARBIERU D, BELIGAN D, IONITA A (eds) Proceedings of the 11th International Scientific Conference on eLearning and Software for Education Bucharest, April 23 - 24, 2015, pp 133–141,

Fuchs P (2017) Virtual Reality Headsets. London: CRC Press

Gao P, Datao Yang, Ming Shen, Xiaozhong Guo, Huanhuan Yu, Zhao Y, Xu Z (2011) Space situation simulation and visualization based on ogre. In: 2011 Eighth International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), vol 4, pp 2566–2569,

Gibson J (1979) The ecological approach to visual perception. Boston: Houghton Mifflin

Gorman I (2020) 5 vr space travel apps: Explore the cosmos with virtual reality space travel. URL https://appreal-vr.com/blog/virtual-reality-space-travel/, last visited in February 2020

Greenwald SW, Kulik A, Kunert A, Beck S, Fröhlich B, Cobb S, Parsons S, Newbutt N, Gouveia C, Cook C, Snyder A, Payne S, Holland J, Buessing S, Fields G, Corning W, Lee V, Xia L, Maes P (2017) Technology and applications for collaborative learning in virtual reality. In: Smith BK, Borge M, Mercier E, Lim KY (eds) 12th International Conference on Computer Supported Collaborative Learning, CSCL 2017, Philadelphia, Pennsylvania, USA, June 18-22, 2017, International Society of the Learning Sciences, URL https://repository.isls.org/handle/1/210

Grivokostopoulou F, Perikos I, Hatzilygeroudis I (2016) An innovative educational environment based on virtual reality and gamification for learning search algorithms. In: 2016 IEEE Eighth International Conference on Technology for Education (T4E), pp 110–115,

Hite R, Childers G, Jones MG (2018) Review of Virtual Reality Hardware Employed in K-20 Science Education. Springer Berlin Heidelberg, Berlin, Heidelberg, , URL https://doi.org/10.1007/978-3-642-41981-2_123-1

Ip HSH, Li C, Leoni S, Chen Y, Ma K, Wong CH, Li Q (2019) Design and evaluate immersive learning experience for massive open online courses (moocs). IEEE Transactions on Learning Technologies 12(4):503–515,

Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. The International Journal of Aviation Psychology 3(3):203–220

Kessler D, Cour-Palais B (1978) Collision frequency of artificial satellites: The creation of a debris belt. Journal of Geophysical Research pp 2637–2646

Kim HK, Park J, Choi Y, Choe M (2018) Virtual reality sickness questionnaire (vrsq): Motion sickness measurement index in a virtual reality environment. Applied Ergonomics 69:66 – 73, , URL http://www.sciencedirect.com/science/article/pii/S000368701730282X

Krokos E, Plaisant C, Varshney A (2019) Virtual memory palaces: immersion aids recall. Virtual Reality 23(1):1–15,

Lartigue J, Scoville T, Pham M (2014) Promoting k-8 learning using oculus rift: Employing virtual reality to increase learning outcomes in elementary biology. In: Bastiaens T (ed) Proceedings of E-Learn: World Conference on E-Learning in Corporate, Government, Healthcare, and Higher Education 2014, Association for the Advancement of Computing in Education (AACE), New Orleans, LA, USA, pp 1100–1105, URL https://www.learntechlib.org/p/148954

Letizia F (2015) Space debris cloud evolution in low earth orbit. PhD thesis, University of Southampton

Lewis JR (1995) Ibm computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. Int J Hum-Comput Interact 7(1):57–78, , URL http://dx.doi.org/10.1080/10447319509526110

Liao M, Sung C, Wang H, Lin W (2019) Virtual classmates: Embodying historical learners' messages as learning companions in a vr classroom through comment mapping. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 163–171,

Likert R (1932) A technique for the measurement of attitudes. Archives of psychology

Lourdeaux D, Afoutni Z, Ferrer MH, Sabouret N, Demulier V, Martin JC, Bolot L, Boccara V, Lelong R (2019) Victeams: A virtual environment to train medical team leaders to interact with virtual subordinates. In: Proceedings of the 19th ACM International Conference on Intelligent Virtual Agents, ACM, New York, NY, USA, IVA '19, pp 241–243, , URL http://doi.acm.org/10.1145/3308532.3329418

Lugrin JL, Latoschik ME, Habel M, Roth D, Seufert C, Grafe S (2016) Breaking bad behaviors: A new tool for learning classroom management using virtual reality. Frontiers in ICT 3:26, , URL https://www.frontiersin.org/article/10.3389/fict.2016.00026

MAGNOPUS (2020) Mission ISS. URL http://missioniss.magnopus.com/, last visited in February 2020

Makarova I, Khabibullin R, Belyaev E, Bogateeva A (2015) The application of virtual reality technologies in engineering education for the automotive industry. In: 2015 International Conference on Interactive Collaborative Learning (ICL), pp 536–544,

Manca D, Brambilla S, Colombo S (2013) Bridging between virtual reality and accident simulation for training of process-industry operators. Advances in Engineering Software 55:1 – 9, , URL http://www.sciencedirect.com/science/article/pii/S0965997812001299

Mantovani F, Castelnuovo G (2003) The sense of presence in virtual training: Enhancing skills acquisition and transfer of knowledge through learning experience in virtual environments

McKnight DS (2016) Orbital debris hazard insights from spacecraft anomalies studies. Acta Astronautic (126 (Supplement C)):27–34

McKnight DS, Pentino FRD, , Knowles S (2014) Massive collisions in leo – a catalyst to initiate ADR. In: In 65th International Astronautical Congress, International Astronautical Federation

Microsoft Corp (2020) Galaxy explorer. URL https://www.microsoft.com/en-us/p/galaxy-explorer/9nblggh4q4jg, last visited in February 2020

Mikropoulos TA, Natsis A (2011) Educational virtual environments: A ten-year review of empirical research (1999–2009). Computers & Education 56(3):769 – 780, , URL http://www.sciencedirect.com/science/article/pii/S0360131510003052

Muchoviento Studios (2020) Astronaut vr. URL http://astronaut-vr.com, last visited in February 2020

Nazligul MD, Yilmaz M, Gulec U, Yilmaz AE, Isler V, O'Connor RV, Gozcu MA, Clarke P (2019) Interactive three-dimensional virtual environment to reduce the public speaking anxiety levels of novice software engineers. IET Software 13(2):152–158,

Opaque Media Group (2020) Earthlight: Spacewalk. URL https://earthlightvr.com/, last visited in February 2020

Pardini C, Anselmo L (2007) Evolution of the debris cloud generated by the fengyun-1c fragmentation event. NASA Space Flight Dynamics Symposium pp 1–13

Pardini C, Anselmo L (2011) Physical properties and long-term evolution of the debris clouds produced by two catastrophic collisions in earth orbit. Advances in Space Research pp 557–569

Pardini C, Anselmo L (2014) Review of past on-orbit collisions among catalogued objects and examination of the catastrophic fragmentation concept. Acta Astronautica pp 30–39

Parmar D, Isaac J, Babu SV, D'Souza N, Leonard AE, Jörg S, Gundersen K, Daily SB (2016) Programming moves: Design and evaluation of applying embodied interaction in virtual environments to enhance computational thinking in middle school students. In: 2016 IEEE Virtual Reality (VR), pp 131–140,

Pinto D, Peixoto B, Krassmann A, Melo M, Cabral L, Bessa M (2019) Virtual reality in education: Learning a foreign language. In: Rocha Á, Adeli H, Reis LP, Costanzo S (eds) New Knowledge in Information Systems and Technologies, Springer International Publishing, Cham, pp 589–597

Puttawong N, Visoottiviseth V, Haga J (2017) Vrfiwall virtual reality edutainment for firewall security concepts. In: 2017 2nd International Conference on Information Technology (INCIT), pp 1–6,

Ragan ED, Sowndararajan A, Kopper R, Bowman DA (2010) The effects of higher levels of immersion on procedure memorization performance and implications for educational virtual environments. Presence: Teleoperators and Virtual Environments 19(6):527–543, , URL https://doi.org/10.1162/pres_a_00016, https://doi.org/10.1162/pres_a_00016

Rashid F (2017) Use of vr technology and passive haptics for manpads training system. URL https://calhoun.nps.edu/handle/10945/56170

Reichhardt T (2017) Access mars introduces space exploration for everyone. URL https://www.airspacemag.com/daily-planet/access-mars-introduces-space-exploration-everyone-180967025, last visited in February 2020

Reichhardt T (2020) Virtual tours of nasa centers. URL https://www.airspacemag.com/daily-planet/virtual-tours-nasas-jpl-and-goddard-centers-180959109/, last visited in February 2020

Rossi A, Lewis HG, White AE, Anselmo L, Pardini C, Krag H, Virigili BB (2015) Analysis of the consequences of fragmentations in low and geostationary orbits. Advances in Space Research

Sagardia M, Hertkorn K, Hulin T, Schätzle S, Wolff R, Hummel J, Dodiya J, Gerndt A (2015) Vr-oos: The dlr's virtual reality simulator for telerobotic on-orbit servicing with haptic feedback. In: 2015 IEEE Aerospace Conference, pp 1–17,

Schijven M, Jakimowicz J, Broeders I, Tseng L (2005) The eindhoven laparoscopic cholecystectomy training course - improving operating room performance using virtual reality training: Results from the first e.a.e.s. accredited virtual reality trainings curriculum. Surgical endoscopy 19:1220–6,

Scott E, Soria A, Campo M (2017) Adaptive 3d virtual learning environments—a review of the literature. IEEE Transactions on Learning Technologies 10(3):262–276,

Sevinc V, Berkman MI (2020) Psychometric evaluation of simulator sickness questionnaire and its variants as a measure of cybersickness in consumer virtual environments. Applied Ergonomics 82:102958, , URL http://www.sciencedirect.com/science/article/pii/S0003687019301759

Sharma S, Chen W (2014) Multi-user vr classroom with 3d interaction and real-time motion detection. In: 2014 International Conference on Computational Science and

Computational Intelligence, vol 2, pp 187–192,

Shibata T (2019) Virtual reality in education: How schools use vr in classrooms. In: Bagnara S, Tartaglia R, Albolino S, Alexander T, Fujita Y (eds) Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018), Springer International Publishing, Cham, pp 423–425

Space A (2020) Explore space vr: Air and space in virtual reality. URL https://www.airspacemag.com/virtual-space/, last visited in February 2020

SpaceVR (2020) Experience the awe of earth: Orbit earth through ultra high definition virtual reality floating in a zero gravity tank. URL https://spacevr.co/, last visited in February 2020

Starr CR, Anderson BR, Green KA (2019) "I'm a Computer Scientist!": Virtual Reality Experience Influences Stereotype Threat and STEM Motivation Among Undergraduate Women. Journal of Science Education and Technology , URL https://doi.org/10.1007/s10956-019-09781-z

Stinson C, Bowman D (2014) Feasibility of training athletes for high-pressure situations using virtual reality. IEEE transactions on visualization and computer graphics 20:606–15,

Ström P, Hedman L, Särnå L, Kjellin A, Wredmark T, Felländer-Tsai L (2006) Early exposure to haptic feedback enhances performance in surgical simulator training: A prospective randomized crossover study in surgical residents. Surgical endoscopy 20:1383–8,

Symonds K, Fornarelli D, Mardle N, Ormston T, Flohrer T, Marc X (2014) Operational reality of collision avoidance maneuver execution. Paper Presented at the SpaceOps

Taupiac J, Rodriguez N, Strauss O, Rabier M (2019) Ad-hoc study on soldiers calibration procedure in virtual reality. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 190–199,

Thornhill-Miller B, Dupont JM (2016) Virtual reality and the enhancement of creativity and innovation: Under recognized potential among converging technologies? Journal of Cognitive Education and Psychology 15(1):102–121, , URL https://connect.springerpub.com/content/sgrjcep/15/1/102, https://connect.springerpub.com/content/sgrjcep/15/1/102.full.pdf

Vichitvejpaisal P, Yamee N, Marsertsri P (2016) Firefighting simulation on virtual reality platform. In: 2016 13th International Joint Conference on Computer Science and Software Engineering (JCSSE), pp 1–5,

Vorderer P, Wirth W, Gouveia F, Biocca F, Saari T, Jäncke L, Böcking S, Schramm H, Gysbers A, Hartmann T, Klimmt C, Laarni J, Ravaja N, Sacau A, Baumgartner T, Jäncke P (2004) Mec spatial presence questionnaire (mec-spq): Short documentation and instructions for application. Report to the European Community, Project Presence: MEC (IST-2001-37661)

Witze A (2018) The quest to conquer the space junk problem. Nature 561:24–26

Wu J, Chen G, Chang C, Lin C (2016) Development of virtual-reality simulator system for minimally invasive surgery (mis) using fractional-order vascular access. In: 2016 SAI Computing Conference (SAI), pp 1257–1259,

Yun H, Park S, Ryu J (2019) Exploring the influences of immersive virtual reality pre-service teacher training simulations on teacher efficacy. In: Graziano K (ed) Proceedings of Society for Information Technology & Teacher Education International Conference 2019, Association for the Advancement of Computing in Education (AACE), Las Vegas, NV, United States, pp 2112–2116, URL https://www.learntechlib.org/p/207938

Zhao J, Klippel A (2019) Scale - unexplored opportunities for immersive technologies in place-based learning. In: 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp 155–162,

TABLE 2. Evaluation questionnaire.

Id	Question	Answer Type
Q1	Sex	Male/Female
Q2	Experience with using video games	One out of: • Not at all • Less than 2 hours per week • Between 2 and 4 hours per week • Between a and 7 hours per week • More than 7 hours per week
Comfort and Usability		
Q3	I did not have any problem with moving and activating things in the environment	True/False
Q4	Have you always felt comfortable during the experience?	One out of: • Yes • No, I did not feel comfortable at the beginning but after some minutes I did well • No, I felt comfortable at the beginning but after some minutes I did not feel well • No, I never felt comfortable
Q5	Have you felt comfortable during the experience as a whole?	Range 1-5
Q6	Please add any comment/suggestion you deem useful. In particular, we would like to know what made you feel uncomfortable	Open
Q7	How would you rate the usability of the hand-held device	Range 1-5
Q8	How would you rate the usability of the 3D environment	Range 1-5
Q9	How would you rate the usability of the elements within the environment that can be activated/deactivated	Range 1-5
Q10	How would you rate the usability of the experience as a whole?	Range 1-5
Q11	Please add any comment/suggestion you deem useful	Open
Educational Value		
Q12	How easy was it to understand the initial tutorial?	Range 1-5
Q13	How easy was it to understand the panels meaning?	Range 1-5
Q14	How easy was it to understand the role of the orbiting objects?	Range 1-5
Q15	How easy was it to understand the meaning of the trajectories?	Range 1-5
Q16	How easy was it to understand how the experience worked as a whole? (what the experience is about, where to go, what to do...)	Range 1-5
Q17	Please add any comment/suggestion you deem useful. It would be quite important to know what was MOST UNCLEAR to you	Open
Q18	In your perception, could this kind of experience enrich a traditional university lecture?	Range 1-5
Q19	Would you appreciate lessons with these kinds of enhancements?	Range 1-5
Engagement		
Q20	Overall, did you enjoy the experience?	Range 1-5
Q21	Please add any comment/suggestion you deem useful	Open

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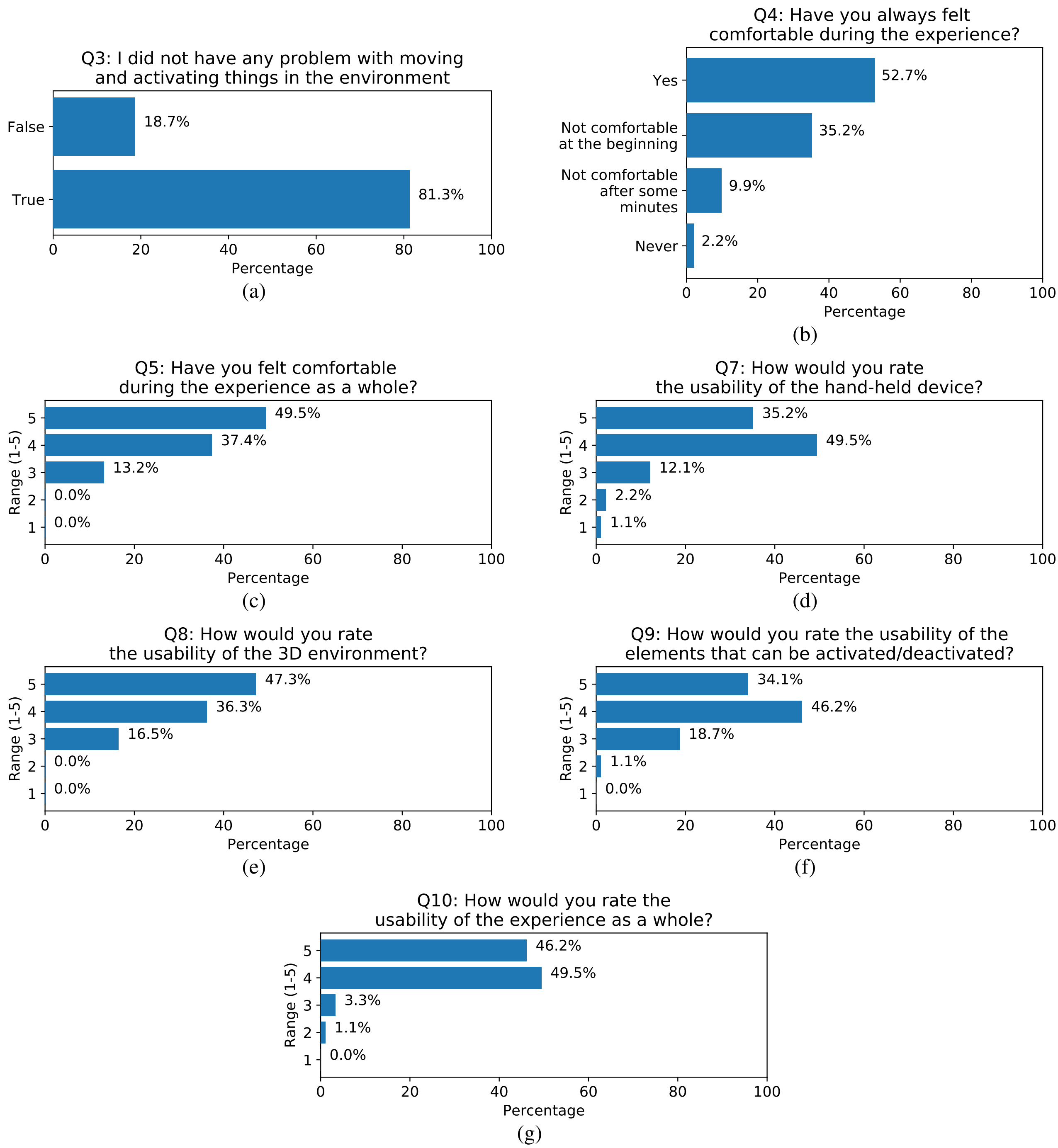

FIGURE 9. Answers to questions about comfort and usability (Q3-Q10).

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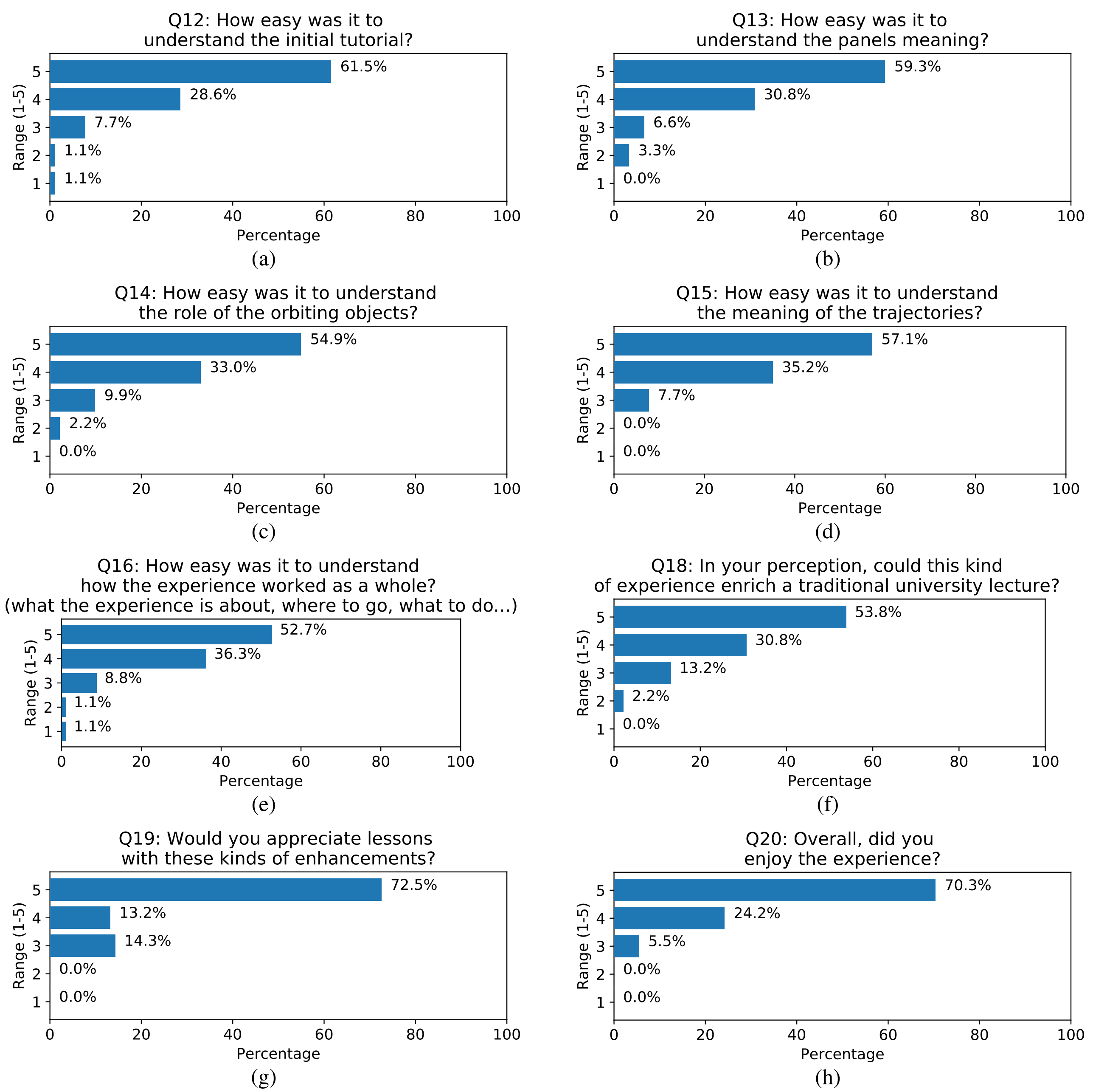
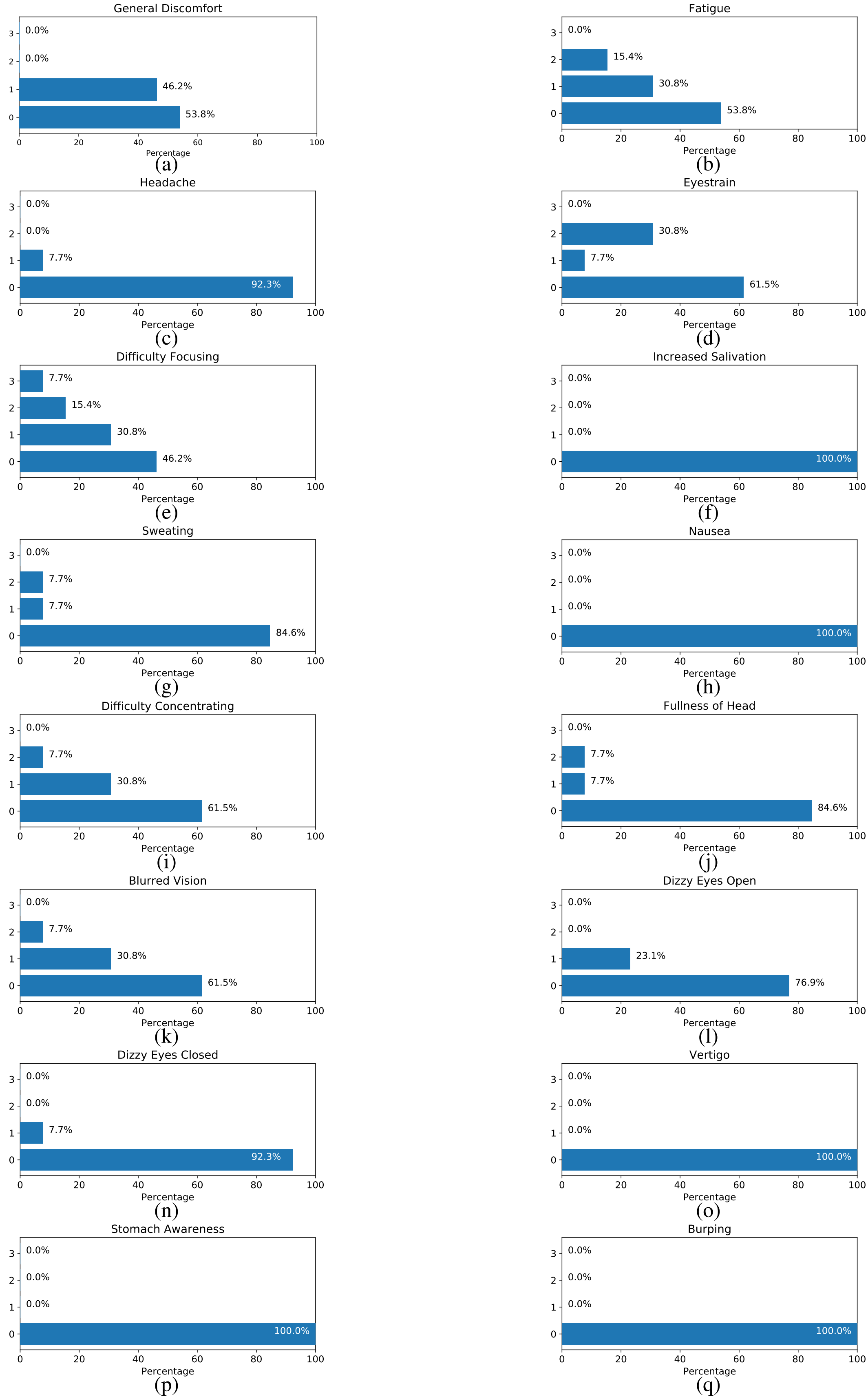


FIGURE 10. Answers to questions about the educational value (Q12-Q19) and overall engagement (Q20) of the experience.

FIGURE 11. Answers to questions from the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993)



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