Overview

Promoting Science, Technology, Engineering, and Mathematics (STEM) is one of the core learning goals in contemporary education. The use of virtual reality (VR) is one approach to engaging students more in STEM, given that it enables immersive learning that one cannot experience in the real world. However, interactivity using VR head-mounted devices (HMDs) is often a solitary experience, cutting users off from the social and learning context of their physical surroundings—collaborating with other students or communicating with instructors. In addition, certain populations may dislike or be discouraged from wearing HMDs, including children, those who wear glasses, and those prone to motion sickness. Therefore, engaging with STEM content through VR is limited in a public setting, such as a museum, by the restricted social interactivity and accessibility of wearing HMDs.

The overarching objective of the proposed project is to develop a socially-connected VR system, MOVIS (**Mo**bile-based **V**R in **I**nformal **S**TEM Learning), and **educational content** with which museum attendees can collaboratively engage with STEM topics using mobile devices (tablets) as a window to a virtual world in a co-located setting. We hypothesize that using mobile devices in a shared space will grant a diverse range of learners access to both the physical world (teachers, peers, and physical surroundings) and a virtual world (educational STEM content) in an inclusive manner, facilitating socially constructed learning using VR. In collaboration with local museums and schools, the team will investigate three research questions: **(RQ1) How can we create a shared learning context in which non-HMD users can experience shared VR and have situation awareness across physical and virtual worlds? . (RQ2) How do the design factors of a shared, mobile-based VR system affect users' social presence, and spatial presence? (RQ3) How does a shared, mobile-based VR space facilitate socially-constructed learning and enable novel active learning techniques in informal learning settings?** To answer these questions, we will develop and assess an interactive exhibit in which learners can engage with planetary science content by employing pedagogical approaches, such as active learning.

Intellectual Merit

The proposed work will significantly advance the state of knowledge in learning science, education technology, and human-computer interaction (HCI). The implementation of MOVIS, a social, immersive, informal learning environment, will produce intellectual contributions as follows. The project will (1) experiment and validate the idea of a shared, mobile-based VR platform for immersive, inclusive, and social VR experiences where learners are exposed to STEM content and VR; (2) investigate the design factors of a social VR system on social interaction and generate design implications; (3) advance understanding of the integration of an emerging technology into socially constructed learning by practicing various informal learning activities in the real world; and (4) introduce accessible VR interfaces and tools, which will open up new opportunities for using VR with more diverse populations and contexts.

Broader Impacts

Our proposed work will have multifaceted broader impacts on diverse populations. First, MOVIS will make STEM content more accessible and engaging in informal learning settings, including museums and schools. This platform will enable various populations, who have often been excluded from wearing HMDs because of psychological and physical issues, to be engaged in immersive STEM learning activities. This will potentially motivate VR researchers and practitioners to make VR more inclusive. The proposed activities will particularly focus on outreach events with two education partners in the local community. The proposed research, specifically, its methods and outcomes will also be integrated in teaching and training of students in PIs' graduate and undergraduate curricula.

1. Introduction

1.1. Motivation and Problem Statement

Virtual reality (VR) technology has enabled unprecedented learning and teaching opportunities. One can create an alternative universe in which learners can be situated in a context that is impossible in the real world: for example, navigating solar systems, watching immune cells and the pathogens battles, and navigating in a Jurassic jungle. Immersive experiences have emerged as effective tools for learners and teachers and have been explored in various settings [1]–[7].

Interaction in VR is often an individual experience, limited to user-system or content interaction. Users of head-mounted devices (HMDs) are generally cut off from the social context of their physical surroundings. It is challenging for others to view what the HMD user is experiencing without additional means (secondary mirroring monitors, a green-screen room). Furthermore, the ways in which non-HMD users—peers, teachers, and bystanders—interact with HMD users are underexplored. This solitary nature of the technology makes it challenging for educators to use it in various learning settings, whether formal or informal. This imposes limits on the rich set of strategies for socially-constructed learning: peer-to-peer communication, active learning, and inquiry-based learning [8], [9].

While all peers, teachers, and their companions wear HMDs to participate in a social VR experience, certain populations dislike or are discouraged from wearing VR HMDs. In particular, there have been concerns that children's use of such HMDs may impact their vision [10]–[12] and motion sickness can be a concern [13]–[15], especially if used for an extended time. In addition to health concerns, some users cannot easily wear VR HMDs or feel uncomfortable wearing a VR headset, including users with thickly textured hair or certain hairstyles [16], those who do not want to ruin their makeup [17], [18], and those who wear prescription glasses [19]. These issues and concerns surrounding VR HMDs significantly hinder inclusivity in using VR for education in practice. One existing solution for sharing VR content as a group is to mirror the egocentric view of a VR HMD user on a central 2D screen that the rest of the group can see. While non-HMD learners can interact with teachers and other learners, viewing someone else's first-person point of view (FPOV) lacks control and agency, as viewers cannot control their view and interact with the content. This approach may also induce cybersickness in viewers [20]. Removing learner control or agency is antithetical to the key affordances of VR as an experience: freedom of viewpoint, movement, and interaction. We are thus in need of VR platforms, where learners can experience a shared, immersive space as a group while allowing natural peer-to-peer communication among participants —instructors, learners, and their companions—in the learning context in informal settings.

1.2. Research Overview and Target Context

We hypothesize that using mobile devices will allow learners to have access to both kinds of worlds: a virtual world (educational STEM content in VR on a screen) and physical worlds (teachers, peers, and other objects outside the screen), facilitating socially-constructed learning in VR and allowing the use of existing pedagogical approaches, such as active learning, cooperative learning, and observational learning. We plan to build MOVIS (**Mo**bile-based **V**R in **I**nformal **S**TEM Learning), a VR platform whose state is shared over mobile devices tracked with six degrees of freedom (6DOF). Learners thus do not have to wear HMDs; instead, they can view monoscopic VR on tablet screens. Our approach to testing this hypothesis will be informed by our previous works in social computing for participation and collaboration (PI Lee), STEM + Art approaches (Co-PI Jeon), immersive technology for situational context (Co-PI Ogle), and informal STEM learning (Co-PIs Newbill and Lyles).

Figure 1. An illustration of the MOVIS platform. Learners can view VR content through a motion-tracked tablet and wander from place to place to explore virtual worlds. A museum educator can explain the content while controlling with or without a VR headset on. Note that the planets in the illustration are only visible on tablet screens and HMDs.

We have chosen science museums as the learning context for our research. A science museum is an informal setting which presents technological and human challenges. Unlike a classroom environment, learner groups are of varying sizes and individuals are of different ages (e.g., young children with family members). Given the diverse range of mixed-age visitors, it is essential that the VR experience be inclusive. In addition, science museum content needs to be presented at various scales, including in smaller settings like after-school programs, temporary exhibits, and small- and medium-sized museums in rural areas. In the envisioned interaction, constructive learning can be guided by in-person museum educators (potentially equipped with VR HMDs), not by a prescripted virtual agent existing only within the VR world. This affords richer interaction between learners and museum educators, and among learners and their companions. In the designed education program, an educator will verbally explain the content, control the VR world as specified in the program, and use active learning strategies (e.g., Think-Pair-Share, Four Corners) to facilitate constructive learning. We anticipate that social connections available in the physical world will draw learners into meaningful experiences with VR content.

1.3. Research Questions

The overarching research question we aim to address in this proposal is how we can create a shared VR environment that can facilitate socially-constructed learning for a diverse range of learners in informal settings. The choice of mobile devices, rather than HMDs, as VR viewers for learners enables us to preserve rich teacher-to-learner and learner-to-learner interactions. More specifically, the following lines of inquiry will drive the proposed work.

(RQ1: Technical Platform) How can we create a shared learning context in which non-HMD users can experience shared VR and have situation awareness across physical and virtual worlds?

To answer this question, we aim to develop MOVIS, a mobile-based, room-scale VR platform in which learners can use handheld devices to experience immersive and participatory media for informal STEM learning. The shared VR space will preserve the spatiality of the real world by giving learners agency to change their view of the virtual world through mobile devices and explore the space. The platform will track the position and the viewing orientation of each mobile device as participants walk around in the virtual/physical space and experience the immersive space with others. The mobile devices will show a monoscopic, interactive VR view on their screens, and their states will be synchronized with other devices in use (HMDs and other mobile devices). To evaluate the system, we will run a series of user studies to assess usability, navigability, and situation awareness. The research contribution of RQ1 will be the concept, design, implementation, and evaluation of MOVIS, a shared, mobile-based VR platform for a co-located setting.

(RQ2: Design Space) How do the design factors of a shared, mobile-based VR system affect users' social presence, and spatial presence?

Facilitating social interaction in co-located mixed reality—a virtual environment on mobile devices and a real environment beyond the screen—is an underexplored research topic. Therefore, it is unclear how the design factors available in a social VR system will affect group interaction and social presence. We will explore various design factors—embodiment, awareness, mixed-device use, and immersion—of the system to answer RQ2 and investigate how they influence their perception of social presence and spatial presence—*the sense of being there*— in the system. The research contribution will be design implications for a shared, co-located VR space for communication and collaboration. These findings are essential in designing educational content for facilitating socially-constructed learning and will be used to inform an interactive exhibit we aim to develop in various settings. In addition, this will advance the state of knowledge in designing a VR platform for social interaction.

(RQ3: VR-based socially-constructed learning) How does a shared, mobile-based VR space facilitate socially-constructed learning and enable novel active learning techniques in informal learning settings?

Finally, we will test our main hypothesis by designing an educational program that can be tested in science museums, pop-up exhibitions, and after-school programs. We will answer this question through an iterative process throughout the project period, consisting of multiple cycles of platform development, content development, learning design, and field study each year, with a MOVIS prototype available at each stage. In particular, we plan to integrate existing (nontechnical) active learning strategies into the platform to assess its ability to facilitate socially-constructed learning with VR-based educational content. In addition, we will explore how the platform enables the use of novel active learning strategies with its positional tracking capabilities and rich interactivity afforded by multitouch screen devices. The research contribution will be an understanding of the effects in VR-based technical intervention and its interaction design on socially-constructed learning.

1.4. Educational Partners

We will work with two educational partners: the Science Museum of Western Virginia, for museum exhibits and after-school programs (with the museum's school partners); and the Institute of Creativity, Arts, and Technology (ICAT) at Virginia Tech, where we will participate in the Science Festival and use ICAT facilities described below.

The Science Museum of Western Virginia (SMWV) has a unique relationship with Virginia Tech, aiming to bring university research to a public audience. The museum delivers K–12 science classes and maintains formal relationships with nearly half of Virginia's K–12 schools, in addition to rural localities in neighboring states. SMWV serves over 90,000 people annually through both its programming and visits to the museum floor, which includes a number of hands-on exhibits developed through collaborations between the museum and university researchers. For Virginia Tech, the partnership supports the pathway of university research to public engagement. For the museum, the partnership provides programming, exhibits, expertise, and interns. Co-PI Newbill is jointly supported by the two organizations and facilitates faculty, students, and staff from both organizations in catalyzing and sustaining this collaboration. The Science Museum of Western Virginia will provide a number of opportunities for the grant team to work with learners to evaluate the learning experience, including camp-ins, day events, summer camps, after-school programs, and school outreach programs.

The grant's second education partner is the Institute for Creativity, Arts, and Technology (ICAT) at Virginia Tech, which connects the project team with physical infrastructure and programming opportunities. ICAT is home to the Cube, a one-of-a-kind, building-scale immersive environment with cyclorama projection, a multiscreen display, a 128-speaker sound system, and motion capture systems (Figure 2-Left and -Middle). The Perform Studio is a room-scale immersive environment with smaller settings (multichannel audio, motion capture system and dynamic lighting). We will use the Cube and the Perform Studio as spaces for developing MOVIS, testing its scalability, developing cross-platform content, and exhibiting the content. ICAT also houses the Center for Educational Networks and Impacts (CENI), which hosts the annual Virginia Tech Science Festival, an expo-style event attended by 4000–6000 people. Many festival attendees are children between the ages of 5 and 15 from Southwest Virginia (Figure 2-Right). We will deploy the MOVIS platform in the festival. Co-PI Newbill organizes the festival.

Figure 2. ICAT facilities and events. Left and Middle: The Cube, a building-scale immersive environment with reconfigurable space. Right: The Virginia Tech Science Festival hosted by VT and organized by Co-PI Newbill.

1.5. Content Design: Solar System Explorer

To answer the aforementioned research questions, we will develop an interactive exhibit in which learners can experience immersive educational content using MOVIS. To that end, while the MOVIS platform will be capable of offering any kind of VR content, we have identified the solar system as our target STEM topic and will develop an interactive exhibit, *Solar System Explorer*. The exhibit will provide science content that can be tailored to multiple levels—an in-museum exhibit, a pop-up exhibition, or an after-school program—in collaboration with our museum partners. It is worth mentioning that developing novel subject matter is beyond the scope of this proposal. Rather, we selected the solar system as our learning topic because it is a topic which science museums traditionally and commonly cover, and because educators find that it provides rich sources for teaching basic STEM concepts that are useful elsewhere, such as time, velocity, frequency, matter, phase, climate, and seasons, to name a few. It also serves as a starting point to address other timely topics: the limit of natural resources and the runaway effects of global warming. The various scales needed to introduce the topic, ranging from an astronaut (human scale) to the entire system (cosmic scale), makes it an appropriate topic for VR; indeed, many educators have used the solar system to study AR/VR technology in education [21]–[24].

Led by Co-PI Ogle, we plan to run an iterative design process to develop *Solar System Explorer*, testing the exhibit with university affiliates and refining solutions prior to evaluation at the SMWV. The development team will be staffed with a student from Computer Science with VR expertise, a student with domain expertise (in Astrophysics or Aerospace Engineering), a student from Visual Arts for visual asset development, and museum educators from SMWV.

In addition to developing the interactive media for MOVIS, we plan to develop *Solar System Explorer* for multiple technology platforms and physical settings—VR HMDs, MOVIS, and the Cube at Virginia Tech—in the latter half of the project period. Making the software available for multiple platforms will enhance the broader impacts of our research with VR-based STEM content that we can distribute online for free (for use with HMDs) and exhibit to a large audience of young learners in a building-scale exhibit (at the Cube) as part of the Virginia Tech Science Festival. In addition, this may be helpful in identifying technical and pedagogical gaps between platforms of various scales.

1.6. Intellectual Merit

The proposed work will significantly advance the state of knowledge in human-computer interaction (HCI), education technology, and learning science. The implementation of MOVIS, a social, immersive informal learning environment, will produce intellectual contributions as follows:

- Experiment and validate the idea of a shared, mobile-based VR platform for immersive, inclusive, and social VR experiences where learners are exposed to STEM content, VR, and multimodal interfaces.
- Explore the design space of a social VR system on social interaction and generate design implications.
- Advance understanding of the integration of an emerging technology into socially-constructed learning by practicing various informal learning activities in the real world.
- Introduce accessible VR interfaces and tools, which will open up new opportunities for using VR technologies with more diverse populations and contexts.

2. Related Works

2.1. Supporting Learning with Mixed Reality

Virtual reality (VR) presents computer-generated, graphical worlds that create the perception of simulated 3D environments [25]. With its engaging experiences and realistic simulations, VR is commonly used for training and entertainment. VR supports a variety of features that are considered important for learning (e.g., high levels of interactivity, support for active learning, social learning environments) and researchers have also suggested the use of educational VR to help students learn facts, concepts, and abstract principles [26], [27]. Compared with other forms of multimedia, VR has the advantage of providing learners with the feeling of directly interacting with any synthesized location or object. By providing opportunities for learners to view information in meaningful locations, VR can provide situational context, which influences not only what is learned [28], but also one's ability to recall [29].

Despite the proposed benefits and wide variety of educational environments that have been developed, little empirical evidence exists to understand how we can implement shared VR experiences for successful educational applications. Mixed-reality applications targeting facts or concepts must be carefully designed to support the learning process without introducing new distractions [26], [27]. As the design features necessary for educational VR to support learning are not clearly understood, a great deal of research is still needed to successfully leverage the educational benefits of the technology.

2.2. Lack of Shared Spatial Experience with Bystanders in VR

The concept of supporting a *shared* VR experience among users is receiving increased attention in the context of improving situation awareness for communication and collaboration. Most of the time, such shared VR experiences have been discussed in remote setups [29] [30], while much existing learning occurs in co-located setups. The most straightforward way to provide multiple users with individual views of a shared virtual world is the use of personal displays, such as the HMDs mentioned previously. However, one apparent limitation of this approach, especially for learning, is that using VR HMDs isolate the HMD users from their physical surroundings, at least visually, unless everyone wears HMDs and joins the virtual world. However, requiring VR HMDs excludes certain populations who dislike or are discouraged to wear HMDs: children, those with carefully coiffed hairstyles, those who wear makeup, and those who wear prescription glasses.

Recently, researchers have attempted various approaches to create a shared VR experience, which may be applicable to informal learning settings. Many of these approaches focus on the problem of offering bystanders awareness of what a VR HMD user is looking at, and they envision new interactions from the additional screens [30]–[32]. However, in this case, bystanders—or non-HMD users—do not share the same spatial representation of the space with the HMD user, limiting their interaction to a smaller scale (typically one-on-one). A few recent works explore allowing HMD and non-HMD users to share a physical space with additional displays [33], [34]. In spite of emerging interest in creating a shared virtual/physical space, the resulting space is often limited to a one-on-one scale, rather than a group of users without VR HMDs. One case which supports a group of learners watching the same VR content in synchronization uses three degrees of freedom (3DOF) HMDs and they can communicate verbally, but this setup limits their shared spatial understanding and active learning [35]. Our proposed work aims to implement a room-scale VR with 6DOF-tracked tablets, where learners can walk around and explore in the shared VR space. Having this spatial representation of a shared VR space can facilitate agency and exploration, thereby further increasing immersion and engagement for users.

3. PIs' Prior Works

(**Audience Participation Music Using Mobile Devices) PI Lee** has worked on various types of collaborative and participatory systems. In particular, he has worked on interactive music pieces that enable large-scale audience participation, where the audience's mobile devices are the only musical instruments [36]–[39]. The networked musical instrument software was designed to facilitate social interaction among audience members. This approach has been validated in the real world, involving a total of more than 600 people across seven live performances (see Figure 3-Left). In addition, PI Lee has worked on various real-time creative collaborations in co-located settings [40]–[42] and online settings [43]–[45], including collaborative AR for prototyping and brainstorming [46].

(**STEAM-based Community Engagement)** To make STEM learning more accessible, **Co-PI Jeon** has worked on projects that integrated STEM content with arts and design, turning STEM into STEAM (STEM + Art). For example, Jeon's team created and ran two after-school programs known as "Child-Robot Theater" at a rural elementary school over two years, with 37 children in total [47]–[54]. In the program, the team included science, robotics, and computer science content with acting, dancing, singing, and drawing inspired by the theatrical production. Another effort to make more accessible and engaging informal learning environments was studying sonification for use in interpretation of live aquarium exhibits, in collaboration with a local aquarium for people with vision impairments [55]–[57]. Jeon's team also created a room-scale immersive interactive visualization and sonification platform, using a motion tracking system [58]–[60]. The platform enabled interactive, immersive performing arts where artists wore sensors while their movements were tracked and sonified over a surround-sound speaker system for multimodal immersion [61] (see Figure 3-Middle). We believe our previous works will serve as a basis for devising the MOVIS platform for learners' embodied, immersive experiences.

(Cyberlearning and VR) Co-PI Ogle has explored the use of immersive experiences to provide situational context in a variety of learning contexts, from decision-making in athletic simulations and visualization of historic sites in embodied VR with passive haptics [62], [63] to using augmented reality to support historical inquiry at the site of the Christiansburg Institute, an abandoned African-American school [64], [65]. CI Spy is a mobile AR application that provides access to a local historical site by presenting virtual representations of buildings and evidence in the context of the site (Figure 3-Right). The results of testing with 14 fifth-grade classes revealed promising results for students' understanding of inquiry and their appreciation of the history of the CI. Additionally, Ogle has collaborated with researchers from multiple disciplines to create AR/VR based museum exhibits and art installations.

(Broadening Informal STEM Learning) Co-PI Newbill has extensive research experience in various informal STEM learning environments, such as museums and exhibitions [118]–[123]. Her research also explores using AR/VR at historic sites and in virtual exhibitions [66], [67]. Since 2016, Newbill has served as a liaison between the university and the Science Museum of Western Virginia. In this role, she is embedded in both environments and understands the cultural norms, timelines, and constraints of these related worlds. Co-PI Newbill is well prepared to guide the project toward successful experiences with learners of all ages in science museums and science festivals. **Co-PI Lyles**'s scholarship explores the intersections of education policy and finance, teaching, and assessment of student learning. Her prior research includes mixed-methods work on broadening participation in STEM by examining the impact of funding and recruitment practices on women and underrepresented minority students [68]. Her research on the application of evaluation education to co-curricular programming and rubric development for formative assessment in academic settings will prepare her for successful participation in the project.

Figure 3. PIs' prior works. Left: PI Lee's audience participation piece using their mobile phones. The piece was performed in the Cube 2019. Middle: PI Jeon's immersive environment with spatial audio and motion tracking. Right: In PI Ogle's work on historic inquiry using AR, a student uses "X-ray vision" to peer inside a derelict building on campus.

4. Research Plan

Our research will comprise three main efforts corresponding to the three research questions presented in section 1.3. In this section, we present detailed plans for those efforts.

4.1. RQ1: Developing a Shared, Virtual Space with 6DOF Mobile Devices

(RQ1: Technical Platform) How can we create a shared learning context in which non-HMD users can experience shared VR and have situation awareness across physical and virtual worlds?

(Overview) The main purpose of this proposal is to facilitate socially-constructed learning through VR in an informal setting, namely a science museum. The prerequisite for this goal is to create a platform that can enable an inclusive, social VR space. To that end, we will create a VR platform based on mobile devices (e.g., tablets) with which learners can view VR content with 6DOF. This approach will permit them to view VR content on tablet screens without sacrificing the visibility of the physical world beyond the screen. Our use of mobile devices is not only inclusive in informal learning settings, but also logistically straightforward: handing out tablet devices with motion trackers attached is simpler than asking people to wear VR HMDs.

Being in a co-located space as a group creates a shared spatial context, which strongly facilitates natural interaction and communication—both verbal and nonverbal [69]. For the first stage of MOVIS platform development, we will focus on the core functionality of MOVIS; that is, creating a virtual/physical space in which a user can control a 6DOF tablet device for viewing VR content. This means that learners can walk around in the shared hybrid space to explore VR content differently from various positions and orientations. Similar to physical learning environments, virtual objects can be used as the focal points of interaction if learners have a shared physical spatiality in the virtual space [70]. For example, not only can they go to different places to view VR content from a new angle (e.g., looking at the dark side of the moon) but also wander from place to place to see other virtual objects (e.g., Mars, Moon, Jupiter) within the shared space, sharing an experience with other learners around the object. The notion of a shared VR space can facilitate exploration, thereby further increasing social interaction and engagement for users.

(Method) We will use a combination of existing hardware and our custom software to create a virtual/physical hybrid space. First, the virtual space (software) will be implemented using Unity and SteamVR; it will serve as a software platform for building VR content and interface with off-the-shelf VR equipment: HMDs, controllers, dynamic motion tracking accessories (markers/trackers), and stationary tracking devices (often called base stations). We plan to configure a physical space where our handheld devices can be tracked using an outside-in tracking method with a set of base stations [71]. The current plan aims to produce a portable platform which we can temporarily install in any sufficiently large open space. With proper configuration (tripods, crowd control stanchions), any open space can be transformed into a shared VR space where multiple users can be tracked.

We then plan to create an auxiliary device that combines a tablet and a motion tracking accessory, as depicted in Figure 1. The tracker can be attached to the top of the tablet for 6DOF tracking within the designated space, with outside-in tracking (i.e., a VIVE tracker attached to a tablet). Each tracker will be mapped to a virtual camera in the Unity-based VR program; the tracker will determine the position and orientation of the virtual camera through which the tablet's user can see and engage with the VR content. The video image from the virtual camera will be streamed to the tablet's screen using Unity Render Streaming—a WebRTC-based plugin for live streaming rendering on separate devices [72] on our custom web application for further interactivity. Therefore, the physical location of the tablet will determine the location of the virtual camera in the VR environment, and the image that the virtual camera captures will be streamed to the tablet, transforming the tablet into a magic window through which a user can see the VR world. This process is similar to viewing the real world with a camera application on a smartphone screen, except that the tablet screens here will display the VR world instead.

We aim to configure and test the platform to support 10 tablet devices in use simultaneously, considering the computational limits of one PC. Our target number of users is reasonable for the space with tracking. Based on the specifications of two primary VR equipment makers, using four base stations will cover an area of 10 m × 10 m [73], [74], which is sufficient for 29 people, considering social distancing (6 ft apart)

[75]. We anticipate that having a larger number of users in the space would limit their mobility and occlude trackers, preventing the tablets from being tracked accurately. We will test various space configurations in two ICAT facilities: the Cube and the Perform Studio. We will test the maximum capacity of the basic hardware configuration (four base stations and one PC) and the extent to which it can be scaled. In case the basic configuration does not support the target scale (up to 10 tablets), we will run VR applications with extra hardware to distribute the rendering/streaming load and tracking computations to 2 PCs.

In summary, the tangible outcome of this task will be a platform for temporarily transforming an open space into a hybrid virtual/physical space. With the provided tablets, we anticipate users will be able to immersively experience educational content with viewfinder to a VR world.

(Evaluation) For this task, we will evaluate the MOVIS platform as a hybrid space that allows users to access both the physical world and a virtual world through an in-lab experimental study. Particularly, we will assess the platform from two angles: (1) users' ability to navigate the space and view VR content, and (2) their situation awareness in the virtual world and the physical world.

We will compare the 6DOF tablet's navigability—that is, how quickly and accurately users can locate and trace a virtual object with the auxiliary device—with a computer with existing controllers (mouse and keyboard). Study participants will be tasked with locating a virtual object that randomly appears in the space or tracing an object in motion. The dependent measures will include time and errors in locating the target item, as well as the degree of deviation from the optimal route of tracing the target item.

We will also gauge the success of this platform by assessing whether users can gain situation awareness of the virtual world and the real world. Participants will be given a certain task (e.g., playing a Pictionary-style VR game with virtual agents in the VR world) and asked some questions about the real world and the virtual world in various conditions (viz., a HMD user's first-person POV on a secondary screen versus MOVIS). There are three levels of situation awareness: perception (sensory-level detection), comprehensive (interpretation of the meaning and significance of the situation), and projection (prediction of future states) [76]. Three levels of questions will be developed to assess participants' situation awareness in both worlds, based on the Situation Awareness Global Assessment Technique (SAGAT) [77], widely used situation awareness measurement method. In the experiment, there will be both real-world and VR objects that can be used to develop a questionnaire.

For both experiments, in addition to defined performance measures, we plan to observe the entire study to understand users' behaviors and any emergence of group behaviors. We will iterate two rounds of user study at the individual level (one participant per session) and at the group level (four to five participants per session, tasked with collaboration). In total, we aim to have 30 sessions (20 individual, 10 group) for each round.

4.2. RQ2: Investigating the Design Space of a Shared, Mobile-based VR Space

(RQ2: Design Space) How do the design factors of a shared, mobile-based VR system affect users' social presence, and spatial presence?

(Overview) For the second task, we will focus on investigating the effects of various design factors that are important in VR and groupware on the user experience in the MOVIS system. Particular design factors that we intend to explore include embodiment (e.g., avatars in VR), awareness, immersion, and mixed-device use (HMDs and tablets). We hypothesize that certain design features may have negative impacts on users' overall experiences, especially in the context of group interaction in a co-located setting. For example, it may be difficult for an educator to attract the attention of a learner who is deeply immersed in the VR content. Or, an educator wearing a VR HMD may find it easy to control virtual objects compared to using a tablet, while identifying random bystanders in the same physical space may be challenging with the HMD on. Lastly, guiding learners' attention to a virtual object can be challenging when there is nothing in the air in the physical world, thereby necessitating awareness cues in the VR world. It is essential to explore this rich design space of the mobile-based, shared VR platform before deploying the system in a learning context. The findings from RQ2 will inform us on how to design and develop an interactive exhibit that provides a seamless user experience for both learners and educators, especially given that they will be encouraged to interact inside the system and outside the system. Through the iterative and explorative design, development, and evaluation process, we aim to identify design implications for supporting group interaction in the MOVIS platform by evaluating the impact of various design factors on two dependent variables: social presence and spatial presence.

(Method) For this task, we outline the design factors of interest and introduce our plan to explore the design space defined by such factors.

Embodiment: We will explore various methods to visualize learners and an educator within VR content: minimal (device-only) embodiment, avatars, and overlaying real-world visuals on the VR scene. Visualizing users with avatars in VR can not only enhance their sense of self-presence, but also strengthen social presence between users [78], [79]. Having no embodiment of users may seem strange, but it can also be beneficial in viewing VR content, as users' VR views will be less occluded. One technical challenge we face in embodying tablet users is that the position and orientation of a tablet is the only information available to the system to utilize for visualization (e.g., a child may be standing and holding a tablet while two adults sitting on the floor are sharing a tablet.). We plan to develop a visualization technique which can approximately visualize a tablet user. We plan to first identify heuristics from an observational study and develop a rule-based classification algorithm that can be used to render a simplified avatar.

Awareness: The second design factor that we aim to investigate is gaze awareness for fluent communication. As tablet users will not have peripheral awareness due to the limited field of view (FOV) available on the screen, it will be challenging for them to notice events in the virtual world until they orient their tablets correctly. Deictic hand gestures by a user (e.g., an educator) may be still ambiguous, as the target object may be anywhere along the pointing direction. This limitation is critical in learning contexts, as an educator will sometimes need to draw learners' attention to a certain position in a VR system while verbally explaining the content (e.g., "Check out this black dot on the surface."). An educator should be able to highlight the spot they would like learners to look at, and to guide them in case the highlighted spot is outside the learners' FOV. Guiding users' attention has been a topic of growing interest, and researchers have attempted to use various cues (visual cues, side views, auditory cues, reorientation) [81, 82], though mostly in concert with 3DOF VR devices in a solitary setup. We plan to develop awareness cues in a setting where multiple users can be guided to locate what a specific user is pointing at.

Mixed-device use: While we will provide motion-tracked tablets for learners, an educator may benefit from wearing a VR HMD, which would afford them a full embodied avatar, 3D user interaction, and fluent control of 3D objects. Nonetheless, an educator may also benefit from using a tablet and seeing their physical surroundings: a non-tablet user, a family sharing a single tablet, or visitors' facial expressions. We will explore various options to address these issues, including a tablet that has different functionalities from the ones that learners use, an inside-out tracking HMD for object detection, and a video see-through HMD that allows the wearer to see other people's real bodies.

Immersion: While increasing immersion is a typical virtue for VR systems, it may not be so in our case, as the system aims to facilitate social interaction outside VR as well. For example, learners may be asked to do Think-Pair-Share. We hypothesize that there exists a tension between immersion and moderation of educational programs, and we study such a tension by enhancing immersion of the MOVIS platform and how it affects user experience. Immersion is defined as the objective level of sensory fidelity a VR system provides [80]. We increase immersion by intersensory integration; that is, by including auditory and haptic sensory input, based on previous works [81]–[86]. Various sounds that match the content introduced in *Solar System Explorer* will be played through a speaker array: the sound of a rocket launch, a simulation of the difference between sounds on Mars and Earth, or the audio from the original footage of the 1969 Moon landing, for example. In addition, sonification of cosmic phenomena (e.g., eclipses, meteorites, the revolutional velocity of the Moon) can effectively convey information that cannot be presented on a small screen. We plan to play these sounds through a 3D audio system in the Cube and the Perform Studio. We will determine whether to include 3D audio systems in the final MOVIS platform. In addition to the 3D audio system, each tablet can be used for giving individual auditory feedback and playing local sound events in the space, such as to render the sounds of satellites moving along a certain path. Furthermore, each tablet will be used as, or augmented with, a haptic device that will vibrate in response to certain events in the content. While all the learners are holding the devices, the central system can signal each tablet depending on its location. This can offer individualized haptic feedback synchronized with audiovisual events, enhancing the overall immersion level of the system.

(Evaluation) We evaluate these four factors considering two dependent variables: social presence and spatial presence. To that end, we will conduct in-lab group studies that simulate informal learning sessions in the Cube in iterative fashion for each prototype we develop throughout the project period. Note that this is not yet an evaluation of learning effects in the museum context and rather an experimental study which simulates the one-to-many scenario (one educator, many learners). We outline how we plan to measure each dependent variable as follows.

Social Presence: Social presence is defined as "*degree of salience of the other person in a mediated communication and the consequent salience of their interpersonal interactions*." Measuring the social presence between learners and an educator and among learners can effectively show how each design factor can influence the extent to which it can facilitate group interaction. To measure this social presence, we will use the Social Presence Module of the Game Experience Questionnaire [87]. It includes psychological involvement, behavioral involvement, and negative feelings.

Spatial Presence: In the MOVIS platform, spatial presence—*the sense of "being there"*—is a crucial component for users in VR in terms of to what extent users have immersive experience. Therefore, we will measure *spatial presence* using the MEC-Spatial Presence Questionnaire [88] (e.g., attention allocation, self-location, possible actions) after each session. The qualitative feedback from the participants will also be collected in subsequent interview sessions, as well as from observations. Lastly, interaction traces will be analyzed in response to the participants' feedback to understand how MOVIS functioned.

4.3. RQ3: Validating the Effectiveness of MOVIS for Socially Constructed Learning

(RQ3: VR-based Socially Constructed Learning) How does a shared, mobile-based VR space facilitate socially-constructed learning and enable novel active learning techniques in informal learning settings?

(Overview) Following the technical validation and design exploration of MOVIS through RQ1 and RQ2, the alignment between its implementation and learning in museums will be validated in a real-world setting, the Science Museum of Western Virginia and ICAT-hosted events. The system's inherent social nature is expected to be effective in facilitating socially constructed learning. To verify its effects, we will create an education program that incorporates various active learning strategies into the use of the MOVIS platform. Active learning requires a learning environment that aligns with constructivist strategies and urges students to socially discover, construct, and produce new understandings [9]. The primary objective of this task is to create meaningful learning interactions among learners, between learners and the museum educator, and between learners and the content. As stated in 1.5, the learning content, designed in collaboration with our science museum partners and subject matter experts, is a prerequisite of the following activity. The developed content—both technical and pedagogical—will afford a range of learning activities, roles and interactions. The intent of the interactions will be to engage learners in active questioning, as well as role-playing and experimentation.

(Method) We will verify the effects of MOVIS in facilitating socially-constructed learning by validating the following hypotheses: (1) active learning techniques can be seamlessly integrated into the educational program designed for MOVIS, and (2) the MOVIS platform affords novel active learning techniques. We plan to test these hypotheses throughout the project timeline.

<u>Nontechnical Intervention:</u> Regarding the first hypothesis, we will integrate active learning techniques that require minimal technical intervention and evaluate the learning outcome. We plan to test simple techniques (e.g., Question-and-Answer, Think-Pair-Share, Polling—using tablets as clickers [89] or standing in each corner of the space) and comparatively complex ones (e.g., Jigsaws). For example, the Jigsaw team technique can be used for a question asking “What makes the winter in Virginia cold?” or “How do you think the weather in Australia will be in December?”, facilitating them to construct the meaning of seasons in relation to Earth’s rotation, revolution, and their axis difference. This activity will allow us to understand how active learning can be integrated into VR-based informal learning settings.

<u>Technical Intervention:</u> In addition to integrating active learning techniques, we plan to develop novel active learning methods that MOVIS can uniquely afford. We believe that the ways in which tablets in MOVIS are tracked in a shared physical space with the capability of viewing a VR world can enable novel active learning strategies. In that regard, we plan to develop specific active learning activities that are tightly connected to the solar system to verify how MOVIS permits the development of new active learning techniques. Here, we provide a few ideas that can exemplify such functions:

1) An educator can ask learners to “Take a picture of the coldest planet in the solar system”, and learners will explore the space, observe where other learners go, and use the tablet to take a virtual screenshot.
2) A group of three students can simulate different phases of the Moon (e.g., crescent moon, half moon, full moon, lunar eclipse) by having them act as Sun, Earth, and Moon, replicating their movements.

(Evaluation) The goal of museum learning is not only or necessarily to increase specific content knowledge for learners. Rather, museum learning is intended to improve attitudes toward STEM. The following evaluation method is informed by the six strands of informal science learning [117]. *Solar System Explorer* will be exhibited at various events specified in 1.4 using the MOVIS platform as it is incrementally developed (six in-museum events in Year 1, eight events in Years 2 and 3; half of the events in Years 2 and 3 will be after-school programs.). For any field studies—in-museum events, exhibitions, after-school programs—Co-PI Lyles will consistently serve as a project evaluator and provide assessment and evaluation services over the life of the project. She will work with the PI and other Co-PIs to develop an evaluation plan, create a logic model and indicators, and develop an evaluation timeline. Additionally, she will create embedded assessments of learning that align with the *Solar System Explorer* content, develop formative assessments of MOVIS to improve the educators’ and learners’ experience, create and implement data collection structures, analyze evaluation data, and provide annual and summative reports of the evaluation findings over the life of the project. The overarching evaluation questions are:

- How well is educational content delivered in selected informal settings using MOVIS?
- How do museum educators manage the technology, setting, content, and communications?
- How well do learners socially interact with other learners or museum educators?
- How do learners respond to educator-moderated active learning?

To answer these questions, we employ the mixed-methods evaluation approaches outlined below.

Observational Study: To evaluate learners' engagement, we will employ the Visitor-Based Learning Framework to derive an engagement profile for the design of the immersive museum experience [91]. The evaluator will develop an observation form which she can use to observe and log the field setting.

Embedded Assessment: For young learners, simple questions will be embedded in the software to assess student content learning throughout the session. Their answers will verify whether the content is delivered to the learners. In addition, simple binary questions or emoji response questions which ask about their experience will be embedded in the software. These questions include "Did you make any friends during this activity?" (yes/no) and "Did you enjoy this activity?" with smiley face emoji to supplement other forms of data collection. In addition, the research team will engage the learners in Think-aloud and Think-Pair-Shares, seeking to understand the process that the learners are engaging in to demonstrate their understanding of the subject matter.

Focus Group, Interview, and Questionnaire: We will conduct semi-structured interviews with the trained museum educators, inviting them to respond to their own experiences and those of the learners. The interview will gauge their experience of managing both the technology and the content in the experience. In addition, we plan to follow up with small focus groups with parent/child museum participants. We will conduct a survey of educators and eligible users (companions) to assess system usability with a questionnaire adapted from the System Usability Scale (SUS) questionnaire [90] and new heuristic items identified specifically for virtual reality systems [91].

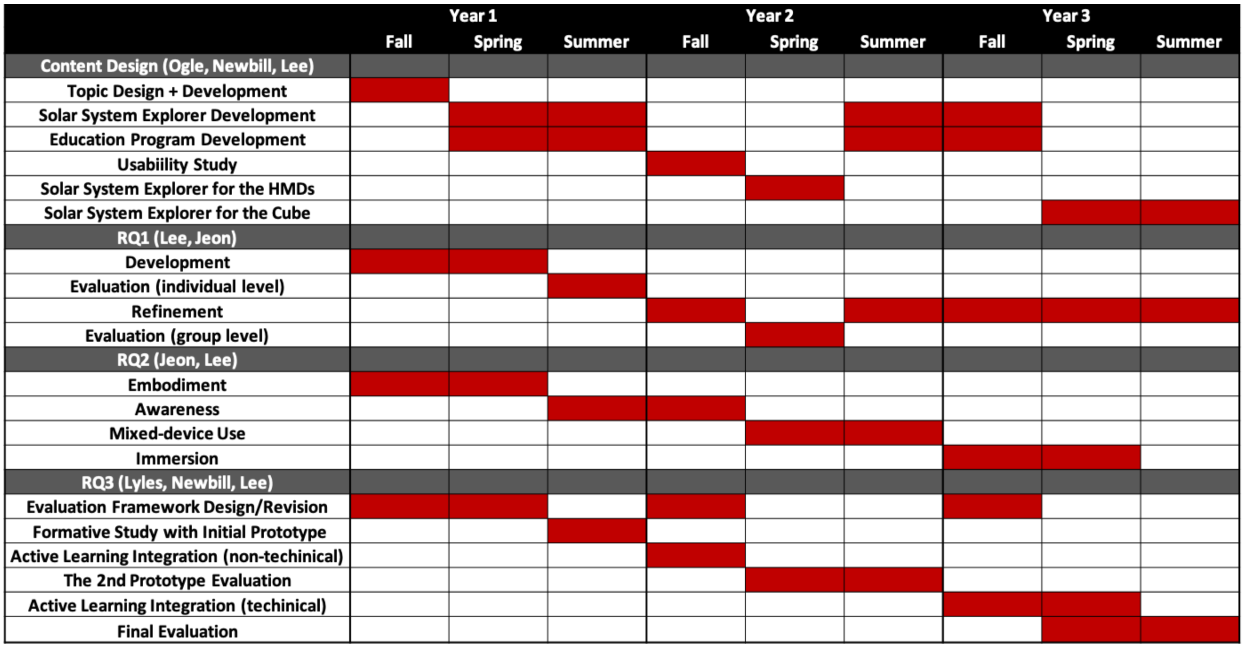
4.4. Advisory Board

We will ask our advisory board to evaluate (a) that our project is on track and achieving its goals, and (b) that we are answering our research questions using a reasonable process. Our advisory board will have biannual advisory board meetings to assess our progress. We have four members on our advisory team:

- Dr. R. Benjamin Knapp, Director of the Institute for Creativity, Arts, and Technology (ICAT) and Professor of Computer Science at Virginia Tech.
- Dr. Doug A. Bowman, Professor of Computer Science at Virginia Tech and director of 3D Interaction Group and the Center for Human-Computer Interaction. He is an ACM Distinguished Scientist.
- Dr. Lisa McNair, Director of Center for Educational Networks and Impacts (CENI). Her work explores the ways teaching and learning can be promoted across different fields.
- Ms. Rachel Hopkins, Executive Director of the Science Museum of Western Virginia.

4.5. Timeline

The timetable for the research proposal is diagrammed below.



	Year 1			Year 2			Year 3		
	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer
Content Design (Ogle, Newbill, Lee)									
Topic Design + Development	🟥								
Solar System Explorer Development		🟥	🟥			🟥	🟥		
Education Program Development		🟥	🟥			🟥	🟥		
Usability Study				🟥					
Solar System Explorer for the HMDs					🟥				
Solar System Explorer for the Cube								🟥	🟥
RQ1 (Lee, Jeon)									
Development	🟥	🟥							
Evaluation (individual level)			🟥						
Refinement				🟥		🟥	🟥	🟥	🟥
Evaluation (group level)					🟥				
RQ2 (Jeon, Lee)									
Embodiment	🟥	🟥							
Awareness			🟥	🟥					
Mixed-device Use					🟥	🟥			
Immersion							🟥	🟥	
RQ3 (Lyles, Newbill, Lee)									
Evaluation Framework Design/Revision	🟥	🟥		🟥			🟥		
Formative Study with Initial Prototype			🟥						
Active Learning Integration (non-techinical)				🟥					
The 2nd Prototype Evaluation					🟥	🟥			
Active Learning Integration (techinical)							🟥	🟥	
Final Evaluation								🟥	🟥

5. Broader Impacts

(Promoting Informal STEM Learning Activities) The foremost goal of the proposed research is to promote informal STEM learning at various sites. Even though STEM education has been emphasized as a cohesive learning paradigm, lowering the barriers to entry for all and recruiting minorities to STEM study are difficult. Moreover, covering STEM concepts and constructs based on the "cognitivism" paradigm is not accessible to the new generation. To make STEM more accessible and engaging, introducing new immersive technologies, such as VR, can be effective. We will implement the MOVIS platform at various events hosted by our partners, which will facilitate STEM education in informal settings.

Our educational partners, SMWV and ICAT, will provide a number of opportunities for the team to work with learners to evaluate their learning experience, including camp-ins, day events, summer camps, and after-school programs. We plan to participate in a total of 22 events as specified in 4.3. In addition, we will participate in various ICAT outreach events, namely the Virginia Tech Science Festival, ICAT Playdate, and ICAT Creativity + Innovation Day, which are open to the public. The audience of the events that we participate in will include students from rural areas of Southwest Virginia.

(Fostering Inclusivity in Emerging Technology Research) One of the core motivations in the proposed research is creating immersive VR environments for a broader population—those who cannot use and do not wish to use VR HMDs. In sum, our proposed work will make the VR experience more accessible and inclusive. The research objective of MOVIS can encourage other researchers and industry professionals to consider the inclusivity of current VR equipment, potentially motivating them to develop ways to include a broader population in using VR. We will host a workshop and tutorials to support and educate early-career researchers and students, and to advocate for a research agenda focused on inclusivity in AR/VR and relevant education technology.

(Impacts on Integrating Research and Education) The proposed research will be integrated in teaching and training young professionals. The requested grant is intended to support at least two graduate students in two departments (CS and ISE) and four undergraduate students throughout the project. PI Lee will include virtual reality projects that can be presented in MOVIS in an undergraduate-level course (CS4644: Creative

Computing Studio) and a graduate course (CS6724: Collaboration, Creativity, and Computing). Co-PI Jeon will integrate the creation of the immersive environment with design factors (sonification and haptic displays) in student projects in ISE3614: Human Factors Engineering Introduction, ISE6614: Human-Computer Systems, and ISE5644: Auditory Display Design. Co-PI Ogle will incorporate the MOVIS platform in the Virtual Environments Studio in the Virginia Tech Library.

(Dissemination Plans) We will publish papers on this work in journals and conferences related to human-computer interaction (HCI), virtual reality, education technology, and learning science. Target journals and conferences include the ACM Conference on Human Factors in Computing Systems (CHI), the IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR), the Association for Educational Communications and Technology (AECT), the American Education Research Association (AERA), and the Immersive Learning Network Conference (iLRN). We will maintain a project website where all software, hardware configurations, event details, workshop materials, and developed workshop materials will be released. Lastly, we will develop *Solar System Explorer* for various platforms, from HMDs to MOVIS and the Cube, and distribute the HMD version online.

6. Results from Prior NSF Support

Lee (PI) and **Lyles** (Co-PI) have no prior support from NSF.

Co-PI Jeon (R01 HD082914-01, 2014/9-2017/5, $692,074, "NRI: Collaborative: Interactive Robotic Orchestration-Music-based Emotion and Social Interaction Therapy for Children with ASD", submitted to and recommended by NSF, and funded by NIH) Intellectual Merit: Co-PI Jeon investigated musical and sociophysical interaction between robots and children with autism spectrum disorders. The efficient system architecture and intervention programs were developed to maximize the children's social engagement and development [53], [92]–[109]. Broader Impacts: This project creates a new pediatric therapy approach using robots to interact with children in a safe and natural manner which can be extended to other pediatric populations. PI has incorporated this knowledge into graduate courses and made outreach programs to promote STEAM education for underrepresented students [47–49, 51–53].

Co-PI Ogle (NSF 1318977, 2013/9-2016/8, $549,039, "EXP: Exploring the Potential of Mobile Augmented Reality for Scaffolding Historical Inquiry Learning"). Intellectual Merit: Developed a mobile AR application (CI Spy) that allows learners to analyze evidence at a historic site. Tests with 14 fifth-grade classes illustrate that students are capable of using AR and VR to transform how they engage with the past as part of a disciplined inquiry [64], [110]–[112]. Broader Impacts: CI Spy and associated learning modules are still in use by the local school division and by the Christiansburg Institute Alumni Group. The project was cited in the U.S. Department of Education's Reimagining the Role of Technology in Education: 2017 National Education Technology Plan Update.

Co-PI Newbill (NSF 1734834, 2017/8-2021/4, $257,205, "Community Cultures: Broadening Participation By Understanding How Rural Communities Support Engineering as College Major Choice") Intellectual Merit: By shifting our focus from students to communities, this research broadens our understanding of career choice by capturing the perspectives of community members who often play a key role in students' decisions, particularly in rural communities [113]–[116]. Broader Impacts: By understanding the ways some economically disadvantaged rural communities support engineering as a career choice, this project is broadening participation in engineering by increasing support for students from these areas.

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