Evaluating Efficacy of VR Technology as a Validation Method for Spacecraft Habitat Design

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DEDICATION

This thesis work is dedicated to Allah the most gracious and most merciful, you were my rock, my refuge, and my source of strength throughout this journey. My success is only by your will. To my loving parents, Gheith and Halima Sasi, thank you is not enough. You both are the reason I made it this far and why I never gave up. Every single time I fell and was stuck you would call knowing something is wrong and pick me up. Even when we were miles away we were never out of touch. For all those double shifts I saw you both work, I never saw you fuss. So even when I was tired I knew I had to keep going to make you both proud. Well I know that I can never repay you both, I am forever grateful for all your sacrifices and putting me first. I hope you both take these words and never have to question your worth.

I would also like to dedicate and thank all the faculty in the Space Architecture department. To Professor Bell, Professor Toups, Professor Kennedy, and Dr. Bannova. Not only did you enlighten me with academic knowledge but also gave me valuable advice whenever I needed it. My evolution as a professional, designer, academic, and as a space architect is from your constant guidance.

ABSTRACT

Spacecraft Habitat Design (SHD) is the process of creating a living and working space for humans outside of our Earth-based environment. A habitat designed for space applications uniquely combines human factors, ergonomics, environmental habitability, technical engineering design constrains, and architectural ingenuity. The unique interdisciplinary requirements of spaceflight make design decisions both time consuming and expensive to evaluate, with severe consequences for poorly made choices that can pose risks to human life and mission success.

With the recent advancements of Virtual Reality (VR) Technology many fields and disciplines that deal with design of engineering large complex designs have used them to their advantage. Such fields being architecture & construction and even the automotive industry. VR technology has not been traditionally been integrated into the SHD process, likely due to the long lead times associated with the spacecraft design cycle, along with the uncertainties and the unknown risks associated with performing evaluations using this yet-to-be proven approach [17]. This thesis aims to investigate the practicality of the use of VR technology as part of a design methodology and evaluation of design, through the assessment of efficacy and efficiency.

This will be done by examining the creation of stereoscopic renderings, walkthrough animations, interactive iterations, and quick demonstrations as explorations of mockups of spacecraft’s and habitats through VR. Experimentation with each visualization method is supplemented with a documentation of the VR scene creation process across an approximated period to measure efficiency, and a set of evaluation parameters to measure efficacy.

This research aims to investigate whether VR can yield the creation of a successful experience that exceeded the time constraints a common SHD mockup walk through (low efficiency) or create a limiting experience where interaction and functionality were not executed to meet the required standards when it comes to evaluating SHDs (low efficacy). Based on the quantitative and qualitative analysis of the two case studies, it was concluded that VR for SHD has high efficiency and efficacy for partial gravity SHDs and low efficiency and efficacy for microgravity SHDs.

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CHAPTER 1: INTRODUCTION

History & Definition of "Virtual Reality"

The first-time virtual reality (VR) was conceived of can be traced back to a science fiction novel called *Pygmalion's Spectacles* by Stanley G. Weinbaum published in 1935. The novel presents a comprehensive specific fictional model for VR. The main character, Dan Burke meets a professor who invented a pair of googles which enabled a movie that gives one sight, sound, taste, smell, and touch - a complete immersive experience. This concept of immersive goggles was also depicted by Morton Heilig's (see Figure 1). His sketched concepts were not materialized, but prior to he built the Sensorama simulator - a multisensory, immersive theater - in 1957 (see Figure 2). The Sensorama included a three-dimensional (3D) stereoscopic display, speakers, haptic feedback through the vibration of the user's seat, and smell. This invention is considered one of the earliest functioning efforts in VR. Later on, Morton Heilig was given the name "Father of Virtual reality" for his invention. His work trailblazed the way for the many features of modern head mounted displays (HMDs). They were built on the same principles of providing a user with binocular 3D visuals and sound [1]. Figure 3 shows a timeline of VR to its current state.

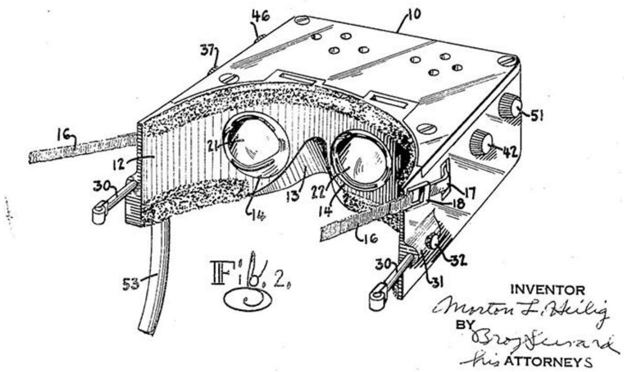


Figure 1: Drawing of Morton Heilig's Specialty "Telesphere Mask" [11]

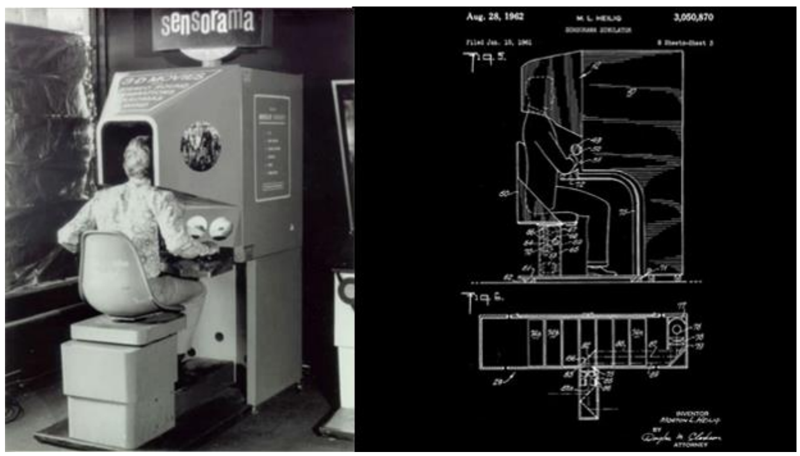


Figure 2: Sketch (right) and picture (left) of the Sensorama simulator [12]

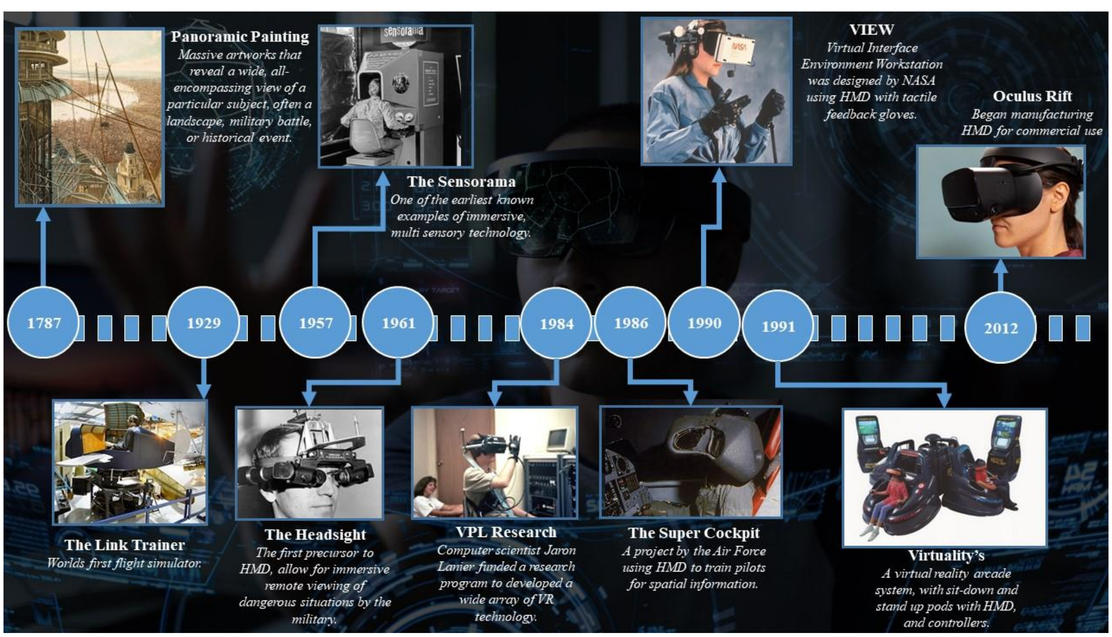


Figure 3: Timeline of historical events surrounding VR technology

The term “virtual reality” can be a bit ambiguous and can have several different definitions. Looking at a more objective definition, the Oxford English Dictionary defines VR as “A computer-generated simulation of a lifelike environment that can be interacted with in a seemingly real or physical way by a person, esp. by means of responsive hardware such as a visor with screen or gloves with sensors such environments or the associated technology as a medium of activity or field of study;” [2]. Vernacularly, the phrase often is regarded as an existential artificial world.

There are a few key factors that are vital for the creation of an immersive experience necessary for VR. While there are different display methods, in this day and age the most popular way is through HMDs. Similar to how the human eyes sees, HMDs uses stereoscopic display to make what you see 3D, and to give depth to the image that you are looking at. However, having a stereoscopic display does not automatically make a 3D immersive environment. The ability to track a user’s motion particularly their head and eye movement allows the image displayed in the HMD to change with your perspective. As the user turns their head the HMD will render whatever image is in that direction. Other than vision, certain VR experiences will include other sensory stimulations like sound and even tactical feedback for touch. Lastly in order to truly alter the perception of our reality there has to be a certain level of virtual interactivity. The VR experience should allow a certain degree of user control navigation such as allowing the user to move forward, backward, or turn through space in the virtual environment. By being able to move freely in a virtual environment and interact within it, the brain can truly perceive the environment is real.

VR has a vast array of practical applications outside of gaming and commercial use. It has been used to train soldiers, pilots, and doctors. VR has seen an exponential growth due to its exceedingly improved technology and hardware from its conception to modern day. Devices like Oculus Rift and HTC Vive have advanced the VR experience by including superior graphics, improved latency, and a wider range of motion. Reduced cost of components is also allowing VR devices to become more affordable for consumer use.

While VR is continuously evolving and showing great promise, there are still some problems to be faced with this technology. One of the main challenges for virtual reality is having a frictionless and pervasive experience for the end user. HMD displays can be uncomfortable for users and at times not user friendly. With many VR applications there tends to be a learning curve for the user to be acclimated to the virtual environment. The success of VR technology will be when it becomes second nature to end users and more intuitive. A design labs visualization leader at Gensler speaks on this: “The problem we are facing with the work that we do at Gensler is the usability of VR, users have to put on a bulky headset and work in it. If VR can get to a point where it can be something very easy to put on and light like a contact lens, this would increase our efficiency” [60].

Having a method of ubiquitous concept to execution is something extremely useful in the realm for designing in large engineering complex systems. In the perspective of spacecraft habitat designers, ubiquitous concept-to-execution VR technology would be as simple as modeling in AutoCAD, Blender, or Rhino to conceptualize and then building a physical mockup to execute the design. VR can achieve a level of ubiquity in allowing spacecraft habitat designers to conceptualize and execute designs in an effortless manner and be more susceptible to integration in the design process. Then VR will truly hit mainstream adoption and be successful in the modern-day human spaceflight industry. For VR to be implemented and have mass adoption, VR technology will need to have less of a learning curve and easier to use functionality. Although current VR technology offers compelling immersive experiences, they have only been in the hands of designers with an interest in early explorations of technological design and VR development. The spacecraft habitat designer's usage of VR depends heavily on the accessibility and ease of the use of this technology, emphasizing the need for VR technological maturity.

Distinguishing Physical, Augmented, Virtual, and Mixed Realities

Alternative reality (XR) is a term used to encapsulate the full suite of human-experience environments that have come to fruition in the modern digital age. Since the invention of digital and modeling environments, researchers have developed taxonomies by which to discuss how the physical world can be altered and enhanced by virtual elements. Five dimensions have been identified and derived from those found in literature and academia. This section will cover those five dimensions: superposition, causality, presence, augmentation, and fidelity. These five dimensions help in distinguishing XR environments, which are physical, augmented, virtual, and mixed realities.

Superposition describes the extent to which knowledge of the environment is virtualized [3]. In other words, superposition characterizes the depth of fusion between the real and digital world. The superposition dimension parallels the Virtuality Continuum as defined by Milgram and Kishino [3]. The Virtuality Continuum is anchored by two extremes, real and virtual environments. Fully real environments have no virtual elements while virtual environments have no real physical elements. It is to be noted that at these two extremes there can be no compromise on the level by which the user experiences his or her environment. Any introduction of the opposing portion of the spectrum draws the defined environment into the umbrella category of Mixed Reality (MR). MR is a broad term and encompasses most environments encountered in the modern digital era.

Causality characterizes the degree of interaction the user experiences within the environment. In this dimension it does not matter if the environment is real or virtual, but rather how information is transmitted and received to and from the user in the environment [4]. Warren Robinett who is well known for his work in automation and human-machine interaction, defines causality in his work [4]. His work has influenced the interaction between humans and machines with XR Technologies. In Figure 4 Robinett describes the synthetic experience. The human user perceives a virtual world which is defined by a possibly changing database called modes, which are four different modes of causality. The first mode, recorded experience, is where the user views a dynamic environment as it is providing additional information to the user, but with no control how and when the experience is altered. Thus, the interaction must be conveyed through a model creating a barrier between the user and the environment. The second mode, transmitted experience, is where the user receives information as in recorded experience but now also directs the interaction. In the third mode, simulated experience, the human views a static environment without any interaction between themselves and the environment. Finally, in the robot experience, the human interacts with the environment without any model interface [4]. Typically for many XR technologies, causality is tied with a recorded or simulated experience, but advancements in technology will allow more transmitted interactions. With physical mockups where the environment has objective existence, there is more of a direct experience between the human and environment. While in a virtual environment it is more of a transmitted experience, it will become more and more objective to the user with advancements in technology.

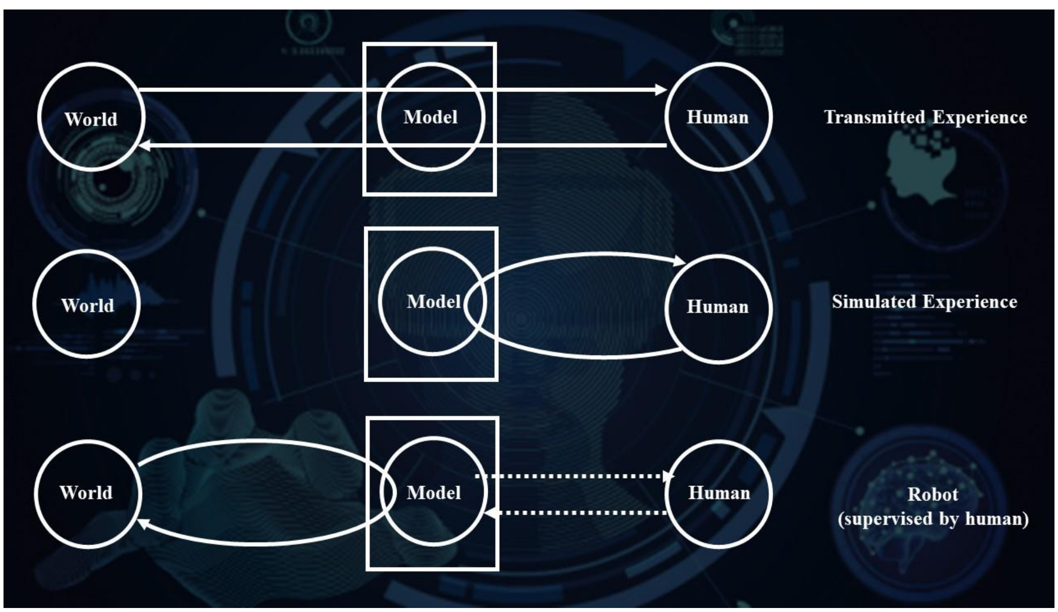


Figure 4: Image depicting the four various modes of Causality [4]

Presence is defined as the extent to which the user feels he or she is occupying the environment. Another word for presence is immersion. In Milgram, Kishino, and Zeltzer research include considerations for virtual realism, metaphors, and multiple sensory systems [4]. The more senses that are stimulated, the user will feel a higher level of presence. Especially within the sensing modalities there are degrees of immersion that can be achieved to influence presence. When it comes design applications and evaluation of design, especially in the engineering application certain sensory systems take priority over others to increase presence. For example, the inclusion of the sense of smell does not have a large effect on the feeling of immersion as the inclusion of haptic response [4]. Bowman and McMahan note that sometimes high level of presence may not be necessary for applications and is an inefficient use of resources to go beyond what is required [6].

Augmentation is the dimension that deals with both the user and the environment, augmentation describes how and where the information about the user and his or her environment is captured and displayed [6]. Augmentation doesn't deal with how the user experiences the environment. Mackay describes three different anchor points for augmentation. The first anchor point is augment user, which is defined by the user carrying a device to obtain information about physical objects. For example, obstetrician can look simultaneously at a pregnant woman and the ultrasound image of her baby inside. A video image of the woman, taken from a camera mounted on the helmet, is merged with a computer-generated ultrasound image that corresponds to the current position of the live image [6]. The second anchor point is object augmented, which is defined as the physical object is changed by input and output of computational devices on or within it. Augmentation of objects is used extensively in education to help students with applied learning. Mackay mentions an example in the early 1970's, Papert created a "floor turtle", actually a small robot, that could be controlled by a child with a computer language called Logo. LEGO/Logo is a direct descendant, allowing children to use Logo to control constructions made with LEGO bricks, motors and gears. Electronic bricks contain simple electronic devices such as sensors (light, sound, touch, proximity), logic devices (and-gates, flip-flops, timers) and action bricks (motors, lights). A child can add a sound sensor to the motor drive of a toy car and use a flip-flop brick to make the car alternately start or stop at any loud noise. Children (and their teachers) have created a variety of whimsical and useful constructions, ranging from an "alarm clock bed" that detects the light in the morning and rattles a toy bed to a "smart" cage that tracks the behavior of the hamster inside [6]. The last anchor point is augmentation of environment, which enhances physical environments to support the user’s activities. In this anchor point information about the user and the physical objects are collected by a 3rd party system and then relayed back to the user. An example of augmentation of environment was Bolt's "Put That There" in which a person sits in a chair, points at objects that appear on a wall-sized screen and speaks commands that move computer-generated objects to specified locations [6]. Mackay displays a table in examples of augmented reality approaches, with relevant technologies and applications in Table 1.

Table 1:Augmented realty approaches with relevant technologies & applications [6]

Augment:	Approach	Technology	Applications
Users	Wear devices on the body	VR HMD Goggles Data gloves	Medicine Field service Presentations
Physical Objects	Imbed devices Within objects	Intelligent bricks Sensors, receptors, GPS, electronic paper	Education Office facilities Positioning
Environment surrounding objects and users	Project imagers and record remotely	Video cameras, Scanners, Graphic tablets, Bar code recorders, Video Projectors	Office work Filmmaking Construction Architecture

Finally, the last dimension fidelity, fidelity describes the degree of accuracy with which the environment captures a true desired representation. It is important to mention that fidelity is measure of comparison between the current environment being worked on the desired product, instead a measure of how “real” an environment can be [7]. Fidelity is independent of the degree to which it is virtualized, unlike superposition which is dependent on the virtualized environment. Fidelity represents the detail which the environment captured in the representation. There is still much debate on an established definition for fidelity. Hays discusses the confusion surrounding the word fidelity, but also provides a meaningful discussion on the definitions of fidelity levels and how it can be broken down [8]. In typical design process in architecture, engineering, and construction fidelity is broken down in high, medium, and low. Walker, Takayama, and Landay discuss the difference between high and low fidelity [9]. Engelberg further describes and discusses mid-level fidelity prototyping, it is more of an obscure category since it can be somewhat left in subjective interpretation [10].

Fidelity is multi-faceted and has many aspects related to it that have been discussed in literature such as equipment, environment, psychological and cognitive, tactical, perceptions, behavior, user interaction, and psychological engagement. Low Fidelity environments both physical and virtual are typically used earlier in the design process due to the fact they lack detail, functionality, and interaction. Low fidelity environments can be used to represent concepts, volumes, and task flows. Medium fidelity environments both physical and virtual as discussed can be quite difficult to define, it lies between both high and low fidelities. It is typically developed in the "middle" of the design process. High fidelity environments both physical and virtual are near exact replicas of the final system or environment and generally realized at a mature design phase; and appear fully functional and interactive from the user's perspective [8,10].

Identifying and deriving these five dimensions (superposition, causality, presence, augmentation, and fidelity) are crucial in order to understand the elements that contribute to XR environments. There is a plethora of implementations captured in these dimensions that is useful to help one identify and classify XR technologies for the average person. Milgram and Kishino provide a Virtuality Continuum to give more clarity to terminology used more broadly for these technologies the classifications are shown along the Virtuality Continuum in Figure 5 are Physical Reality (PR), Augmented Reality (AR), Hybrid Reality (HR) and VR.

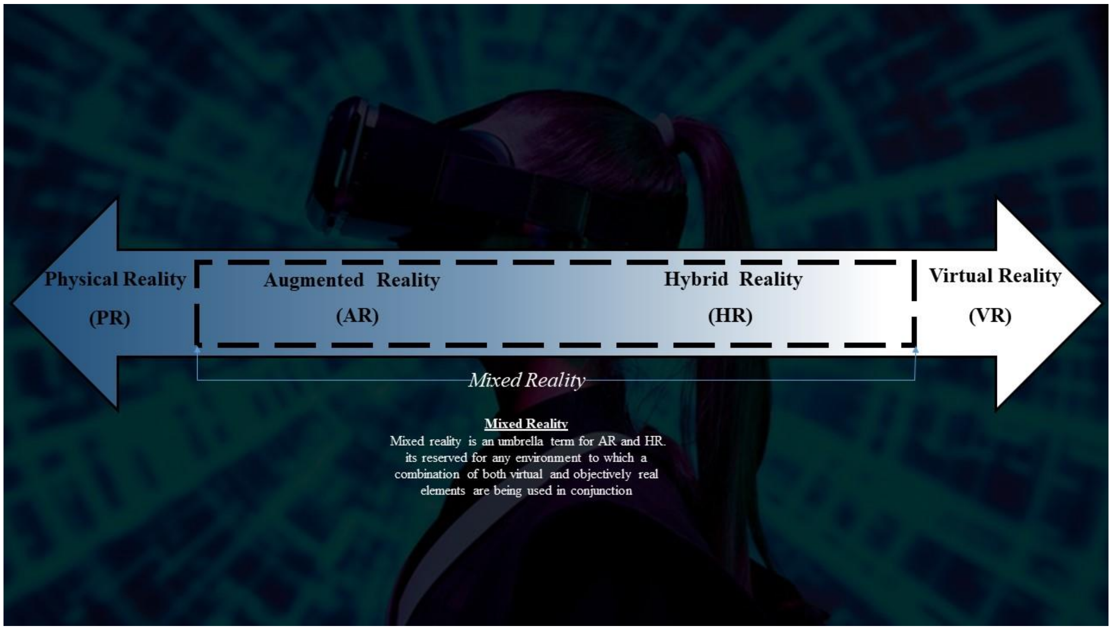


Figure 5: Milgram and Kishino Virtuality Continuum [3]

In It important to note that in Milgram and Kashino Virtuality Continuum they name HR as AR. They mean the same thing, in common vernacular; HR is used quite more often than AR. PR can be defined as an environment with objective existence, it could include digital content but only if that content is reflective of true implementation in the environment. AR can be defined as an environment in one which complements the real world with (computer generated) virtual objects so they seem to coexist in the same space as the real world. It is important to mention that in Milgram and Kishino Virtuality Continuum MR encompasses both AR and HR. In common vernacular “mixed reality” is used to often in place of HR and AR. MR is reserved for any environment to which a combination of both virtual and objectively real elements are being used in conjunction, but it is important to note that this does not imply anything about how much the environment is being virtualized or has real objective existence. MR is a very broad term, can be difficult to use in a way which created a common misunderstanding of what a mixed reality environment means, especially when using this term in engineering and design process. Lastly VR can be defined as a fully virtualized environment simulating any relevant physical aspects. Figure 6 shows the definitions and difference between XR technologies.

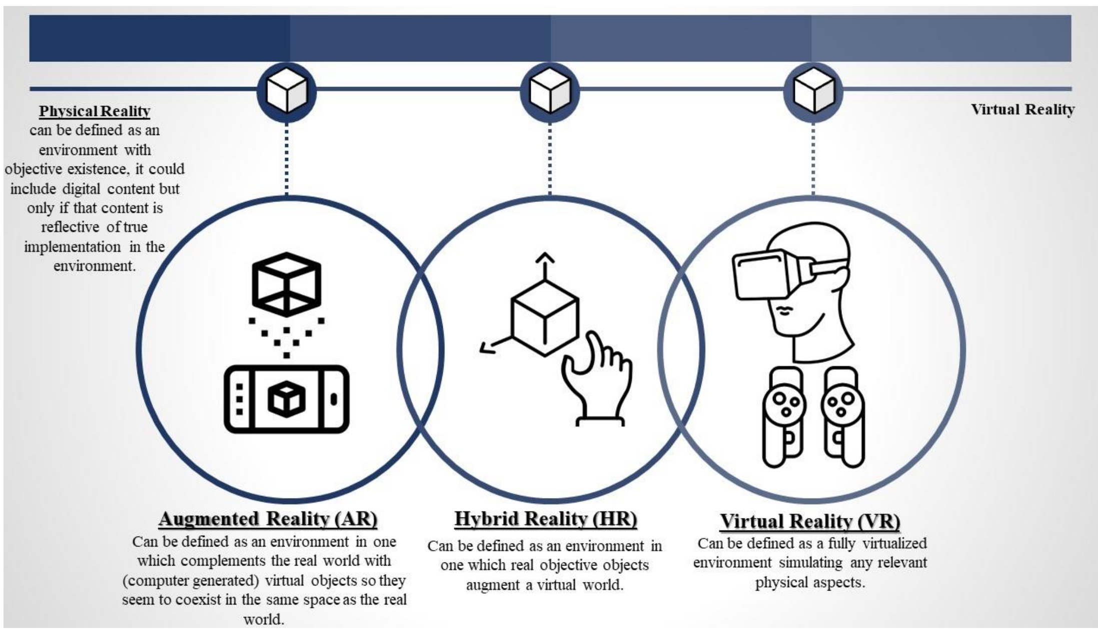


Figure 6: Definitions and differences between PR, AR, HR, and VR

CHAPTER 2: LITERATURE REVIEW

VR's Use in Terrestrial Design and Research Gaps

VR has been implemented and used in a variety of different professions. Currently in architecture, engineering, and construction Building Information Modeling (BIM) is used to aid to help visualize what is to be built in a simulated environment and to identify potential design, construction or operational issues [13]. VR technology is beginning to be used to facilitate site design. With virtual walk throughs, rapid design prototyping, simulating dynamic operations, coordinating detailed design, and marketing designs to customers [14]. The automotive industry has also integrated VR technology to increase quality and cost reducing technology needed for the relatively rapid design cycle [15]. VR technology has led to reduced design and production time and reducing overall costs in early design phases [16]. Figure 7 shows how VR is being used terrestrial in various industries.

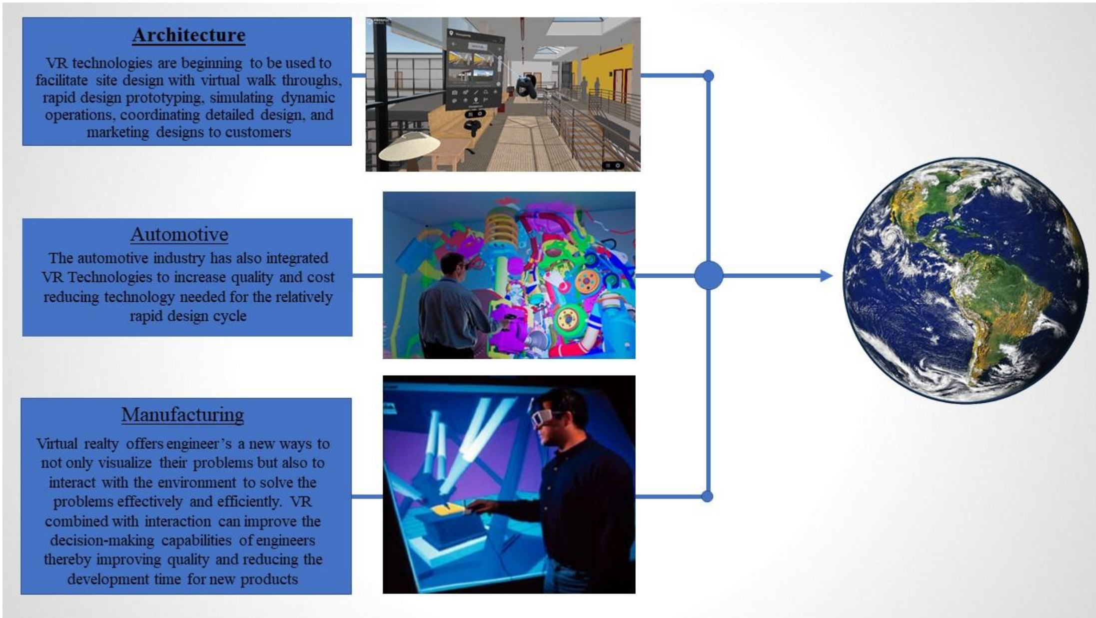


Figure 7: Some applications of VR technology in terrestrial design

VR Technology usage for SHD has been reluctantly not been taking advantage of, even though it has had a lot of success in other disciplines. In a paper titled *Framework for developing alternative reality environments to engineer large complex systems*, it mentions that "XR technologies have not traditionally integrated into the SHD process, likely due to the long lead times associated with spacecraft habitat design cycle, along with performing evaluations using this yet to be proven approach." [17]. From this quote one can see that there is some skepticism behind using VR in the SHD process. Using VR as an evaluation tool for SHD is not bullet proof, this thesis aims to investigate further use of using VR in the SHD process and judging the efficiency and efficacy of it to see if it can become an acceptable approach for design evaluation. There is still a great deal yet to be understood about VR's efficiency and use.

Another research gap is the need for a paradigm shift in the National Aeronautics and Space Administration's (NASA's) overall design process. Table 2 shows the traditional design methods that NASA has currently and the changes that are to be made with the paradigm shift. Figure 8 depicts cumulative percentage life cycle cost against time, where the dotted lines shows were NASA is currently vs the sold lines where it could be in the future with the paradigm shift. Figure 9 shows human system integration (HSI) activities during reviews and life cycle phases for commercial product, department of defense (DoD), and NASA missions. Looking at Figure 8 it shows currently design freedom is low which is bounded time and cost constraints, this makes design knowledge based on assumptions. The goal of this paradigm shift is to give manufactures and designers more freedom to come up with solutions, in other words capabilities. If we can identify possible errors early on because of our increase in design knowledge, then we are able to reduce costs in later phases. There is a need to increase design knowledge, VR technology has the potential to increase design knowledge and add another tool for designers to give a different perspective when comes to tackling designs.

Table 2: NASA's traditional design methods vs the paradigm shift that is needed [18]

Traditional	**Paradigm Shift**
Single-point design, Manual, deterministic process	Dynamic parametric trade environment methods
Single-objective optimization	Multi-objective optimization
Single-discipline, disciplinary-centric analysis	Multidisciplinary approach (analysis, design, and optimization) based on more sophisticated and higher fidelity tools
Uneven distribution of knowledge and effort	Better representation of all disciplines in earlier lifecycle phases
Data driven process	Incorporation of probabilistic methods to quantify and assess risk.
Design space exploration performed around one or a few concepts (point solutions)	Automation of resultant integrated design process
Reliance on historical data, usually full of many assumptions	Physics-based formulations, mainly for new concepts
Fixed design requirements and technology assumptions	Perform requirements exploration. Technology infusion tradeoffs and concept down selections during conceptual design phases
Design for performance	Design for affordability and design for overall Capability

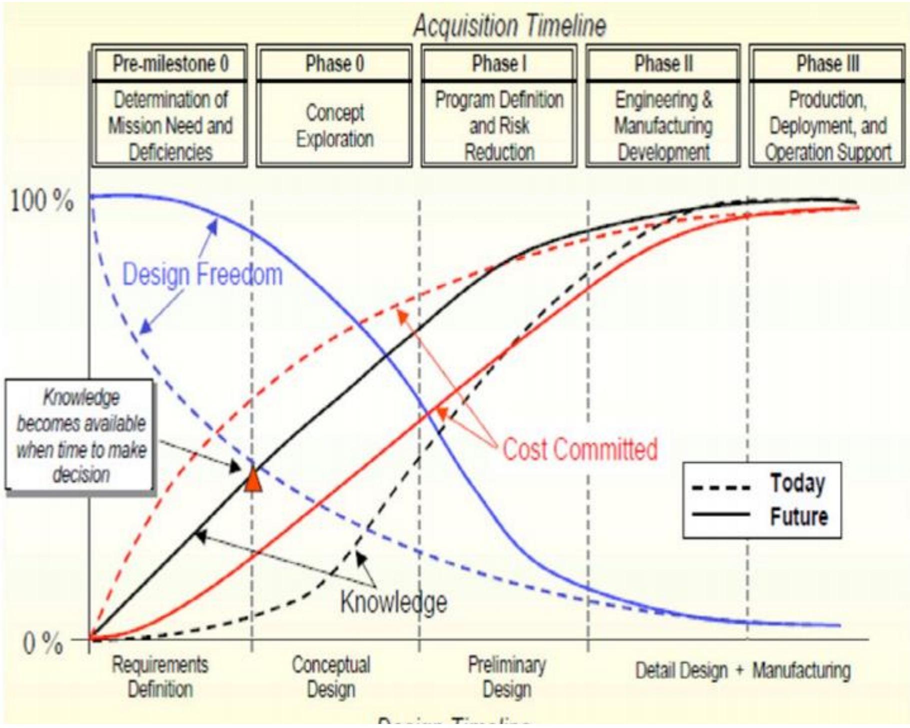


Figure 8: Cumulative percentage life cycle cost against time [18]

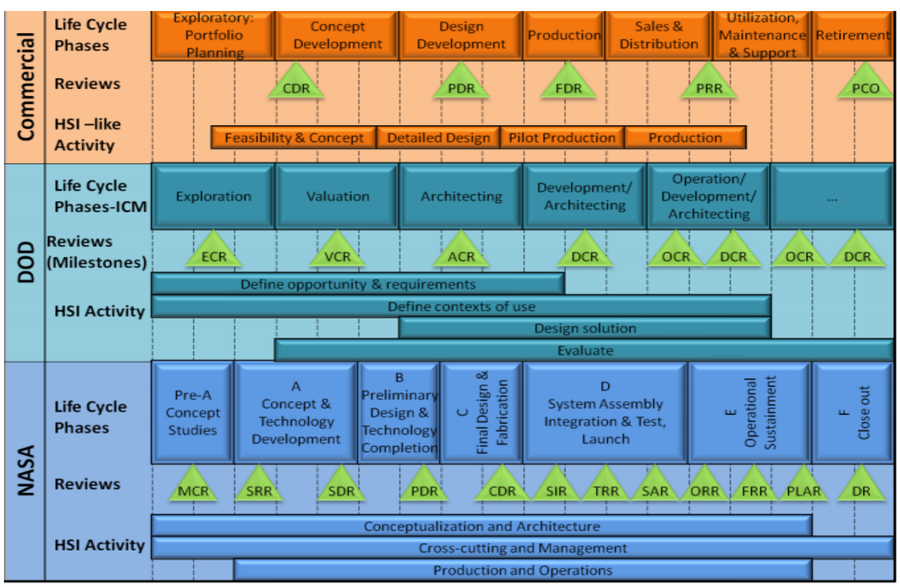


Figure 9: Lifecycle Phases for commercial products, DoD, and NASA missions [18]

Upside and Limitations in Context

In SHD practice, in the initial phases of the project life cycle the purpose is to produce a broad spectrum of ideas for alternative missions. In pre-phase A and phase A is where most of the conceptualization of the design happens. Typically, this is done with engineering drawings, 3D modeling, and digital design tools. Renderings, animations, and walkthroughs are most used in the practice to formalize ideas and communicate the projects with customers and stakeholders. After conceptualization is done used with 3D modeling later in phase C the use of physical mockups is used to get a life like scale of design to test and verify design requirements. This thesis seeks to examine the use of VR with rendering images, and the creation of walkthroughs to understand the full spectrum of visualization features workflow with VR.

Before assessing VR within SHD, one needs to determine the potential upside and limitations of VR technology. This can be achieved by understanding the value it brings to the SHD field. One of the biggest upsides that VR technology brings is that fact that it is able to showcase environments in a life like scale well before they are physically built which is extremely beneficial to communing design specifics in a life like scale. Unlike 3D models which can only be seen on a computer screen, VR has a factor of embodiment; “the state of existing, occurring or being present in a place or thing.” [19]. Embodiment has two factors that contribute to it, one being presence the other being experience. Presence is defined as the feeling of encompassing an environment, activating presence is the brains way of telling the body that an experience is real and that it is different from simply looking at a 3D model on a screen [19]. From a scientific perspective, presence activates the brains motor cortex and the body's sensory system in a manner similar to their activation during a real-life experience. Figure 10 shows an example of how VR simulations stimulate specific parts of the human brain. Secondly embodiment is defined as the experience of real-life scale of objects within the environment [19]. While embodiment brings the sensation of both presence and scale, these factors are tremendously fragile and not necessarily guaranteed for every experience. When done correctly VR has the potential to enhance the project, but the downside is that it can obscure a project when done incorrectly. VR warrants exploration simply since construing a full-fledge mockup is extremely expensive and requires years to formalize. As VR is successful in the creation of immersion and transporting a user to a simulated environments, it present value to designers, clients, and project stakeholders.

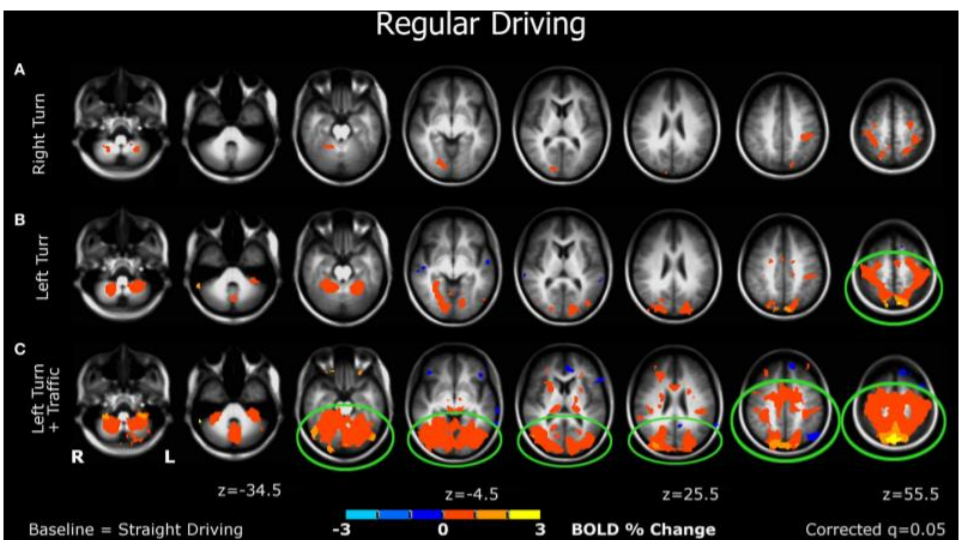


Figure 10: Brain activations from the bottom to the top of the brain (left to right figures) of participants when performing various simulated driving conditions [20]

While VR technology has a big upside to experience a life scale of a design before it is physically constructed, the quality of the experience can suffer due to several reasons. One of the most noted limitations of VR technology is the user experience is not entirely frictionless. The problems that stem from this is loss of presence, unintuitive features and discomfort due to motion sickness. While VR can be used as method to evaluate designs, it could possibly obscure the project and present it in an unflattering light. If the VR experience of the represented design is soured, this could be detrimental to the design being showcased. High end VR experiences requires a tremendous amount of attention to detail along with focus and detail. Creating a VR experience requires a substantial amount of time, effort and expenses which could be a limiting factor. Considering this limitation may explain why VR has not achieved a widespread adoption of higher-end experiences. The upside and limitations of VR in SHD process requires further research.

The ability to view designs (physically and digitally) enables designers to understand spatial relationships by revolving around a design. VR gives another dimension of first-person interaction with the design. The way HMDs affect our sense of perception of a design demonstrates the importance of this technology. VR holds relevance in SHD because perception plays such a crucial role in the way SHD designers, clients, and stakeholders validate a design.

The Relevance of VR in SHD

VR HMDs can have the potential to change the process by the way spacecraft habitat designers can design and communicate their designs during the conceptual stages. HMDs give spacecraft habitat designers an ability to visual immerse in their design. Michael Abrash a chief scientist at Oculus mentions that “The human perceptual system has evolved to capture and process massive amounts of data from our environment, but every form of communication until today has used only a small fraction of that capability, the equivalent of sipping information through a straw. Every medium, from books to video games, provides limited descriptions, from which we have to reconstruct the full experience in our minds, losing the immersive power of reality in the process “[21]. The mediums used to represent design provide a very limiting experience. Books, physical models, drawings, etc. are very limiting experience because the full experience had to be reconstructed in the human mind. With VR technology immersive prowess changes the sense of spatial perception is engaged. In some cases where the human subconscious mind is engaged this causes spatial cognition to be triggered as well [22]. Having the ability to alter the human vision is a huge upside in SHD field. The lenses in VR HMD are responsible for portraying the display to the field of view of the user. At a stroke a person putting on a HMD can be immersed in a three-dimensional environment. This gives a person a greater sense of scale, depth, spatial awareness that is incomparable to traditional drawings, 3D models, and animations.

The intrinsic feeling of truly being inside a SHD space is an extremely valuable asset that VR brings, this is important when it comes too communicating design intent. Often clients and stakeholders don't have the ability to perceive spatial relationships and scale just by looking engineering drawings or 3D models. VR can be a more intuitive and realistic way for a client or stakeholder to interact and understand the design. This added visual dimension could be used to notice aspects of a design that inaccessible by any other method of representation. There are different mediums in the field of SHD for designers to access different views and information of a design. For example, engineering drawings allow SHD to view the connection between different subsystems within the design. Contracting physical mockups of a design enables SHD to understand spatial relationships, human system integration, and human factors relationships in the design at a full scale. The access to another design tool through VR interaction unlocks the ability of first-person interaction with design early in the design process. VR is much more affordable and requires less time to construct than physical mockups. Dr. Robert Howard the habitability domain lead in the habitability and human factors branch at NASA mentions this about VRs potential use in the SHD process "Testing in VR and testing with physical mockups are interchangeable. This is especially useful because in the early design stage we could have many concepts. For most modern organizations it would be challenging in terms of cost, physical space, lack of appropriate hardware and talent to build low fidelity mockups of each of them. But most organizations can build low fidelity VR models of each of them. Instead of making an unsubstantial down selection, you can conduct VR evaluations to down-select to one or more concepts to carry forward to higher levels of detail. There are questions of how far you can go in VR before you really need a physical mockup, but at this early level, it is a definite value-added." [61]. VR has relevance in SHD because of the perception, design knowledge, and design freedom it brings to the table. It plays an integral role the way designers, clients, stakeholders validate assumptions about a design.

The Importance of Presence & Scale in SHD

There are two key components that separate VR technology from any other visualization method, those being presence and scale. These components were mentioned in the previous subsection of upsides and limitations, these components will be discussed in greater depth with relation to the SHD practice in this section. As defined earlier presence is the feeling of encompassing an environment, in this case a virtual environment. Presence transports the user from their objective physical reality into a virtual world. Presence is key component for a user to experience in a VR scene, this aids in providing the user with a positive experience within the simulation. The sense of presence is delicate. When the aspect of presence is lost or lacking with the VR simulation, the experience can be soured. Thus, presence is an integral and relevant to SHD and provides the basis of experiencing a design. The second component scale has a lot of applicability within the SHD practice the experience of a built environment at true scale allows any client or designer to understand the true implications of their creation in objective reality. Whether it’s lunar surface habitation module or a transit vehicle to Mars, experiencing a design is vacuous without the engagement of its actual size. Experiencing any design at true scale is a huge step forward in SHD not only in terms of communicating the design but as well as conceptualizing it and maturing it early in the design process. Designers can thus acknowledge the merit VR has when it comes to showcasing designs, as they may be able to accurately depict dimensions, represent various subsystems, and demonstrate ergonomics of a design. Given the complexity of VR, these two components of presence and scale are not guaranteed in every VR experience. Figure 11 shows the correlation between scale, presence, and embodiment.

A VR simulation can only be as successful as its implementation, which is a challenging task [23]. The objective of VR is the user feels subconsciously present in a virtual world. The human mind has evolved over eons to perceive the objective reality. Being able to present a user a virtual environment that their brain can accept as a subconscious reality during an experience remains the greatest challenge of VR [24]. When VR is executed correctly it can connect SHD to their full power of perceptual capabilities, giving them more design knowledge and freedom with interacting with digital information.

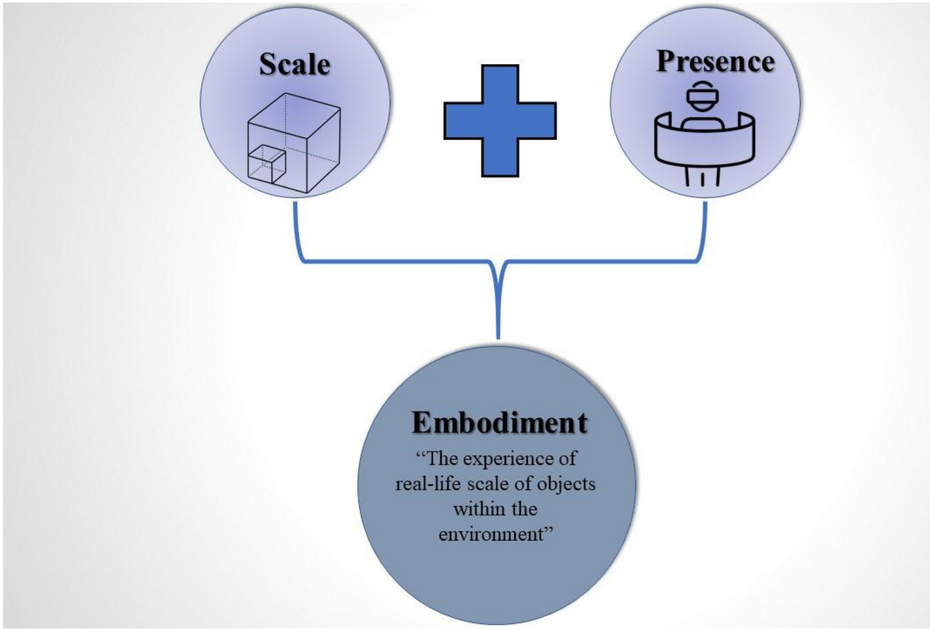


Figure 11: The components that make embodiment

CHAPTER 3: THEORY & HYPOTHESIS

Research Aim & Scope

The aim of the thesis is to evaluate the efficacy and efficiency of using VR technology when it comes to evaluating and investigating SHD. Exploring the upside and limitations that VR technology brings. VR technology can help SHD designers to identify potential problems and success in their work prior to physical construction phase. VR technology applicability needs to be evaluated to be used as an effective and reliable testing substitute when compared against physical mockup structures. Spacecraft habitat designers exploring the creation of VR environments can benefit from learning complex visualization concepts to achieve more autonomy over design and visualization process.

Having the ability to be put in a design and visualize the architecture in real-time is something extremely valuable in the SHD practice. Whether VR is explored through interactivity with design, rendered imagery, or having animated walkthrough. Spacecraft habitat designers now poses another tool to use to give them more design freedom and knowledge. This enables them to expand the possibilities of conceptualization, communication, and verification of their design. Evaluating VR in a design context can allow designers to understand the potential and limitations of the design tool. This thesis aims to understand the design of VR spaces and assessing its use in verifying and validating design. In order to do this, experimentation will be implemented to assess the creation of three outputs of VR technology: rendering, interaction, and walkthrough of the design. It will evaluate the integration of VR in the SHD workflow by using case study models of SHD projects that are created with 3D modeling software's and then importing them into gaming engines. This will be later discussed in the chapter four of this thesis. The technical goals within this process will involve differentiating between building VR scenes in multiple game engines, hardware options, and using different case study models. This will be more demonstrative and give a greater breath of knowledge towards too not only hardware and software uses but also what kind of design project is best used for this technology. With the creation of each experiment, an evaluation will be done with participants to assess the ease of VR technology integration into the SHD process.

Experimentation with Spatial Representation and Neuropsychological Effects of Design

With the emergence of VR technology usage in studies has inspired new opportunities in aiding in development of state of art neuropsychological assessments [25]. VR has aided neuropsychologist to assess and measure more precisely, factors such as users sensor, motor, and cognitive abilities along with behavioral and self-regulatory functions all while users experience in a virtual environment [26]. With VR having success in neuropsychological experimentation, it allows for understanding how positive VR experiences can be created. Although these VR experiences have been conducted in a laboratory setting, it demonstrates the positive VR experiences that were able to sense of embodiment and use it to receive a response from the end user. It can be deduced from these investigations that VR can also aid in spatial understanding and how design effects a person from a neurological perspective.

VR has been used to assess the neurological effects of design for terrestrial design. In a research experiment titled *Evaluating Educational Settings Through Biometric Data and Virtual Response Testing*. The goal of this study was to apply a new approach in examining classroom design innovations by using a protocol to evaluate the effectiveness of classroom designs by measuring the physical response of the study participants as they interacted with different designs using a VR platform. The research aimed to evaluate the effects of building design on human factors such as stress, anxiety and visual memory prior to a building physical construction. They accomplished this by measuring participant's physical and conscious reactions as they interacted with various architectural designs using VR. To obtain the measurements of the physical responses of the participants they were instrumented with noninvasive electroencephalography (EEG) cap to record electrical activity in their brains; electro-oculo-oculography sensors (EOG) to record eye motions; electrocardiogram sensors (EKG) to record their heartbeat; a galvanic sensor response (GSR) unit to record skin conductance; and a tri-axial head accelerometer to record their head motions. The pilot test study from this research showed promising results and demonstrated that collected biometric data has the potential to provide valuable insights about human responses to design variables. They compared activities carried out in a real classroom verses an identical virtual classroom with added windows. Figure 12 shows the activities being done and experiment setup. The data from research indicated that a sharp increase in stress responses during the memory-oriented activities, as compared to the passive baseline. However, the magnitude of the stress responses was smaller in the virtual classroom with windows as compared to the virtual classroom without windows. Another notable finding from the research was that participant's responses were very similar in the real classroom and in the identical virtual classroom. This suggests that virtual replications can possibly be viewed as a suitable substitute for testing the real design [27]. Figure 13 shows the results from the EEG, EOG, EKG, and GSR both from the virtual classroom and physical classroom.

Although this research revolved around terrestrial design it demonstrates a new and practical toolset to evaluate the human impacts of design and could have transferability to SHD. Just like terrestrial design, SHD is a field which focuses on human centered design. Scholars have demonstrated that the characteristics of a built environment can have significant effects on human well-being. Specific design components have been correlated with health outcomes [28]. In SHD this is extremely important when for example when designing a transit spacecraft for long duration missions where crewmembers will be living in for months on end, the design will impact the human wellbeing of these crewmembers. Finding out the neurological impacts of design by using VR prior to construction and deployment could save not only time and money for spacecraft habitat designers but also save the sanity of the crewmembers living inside the design.

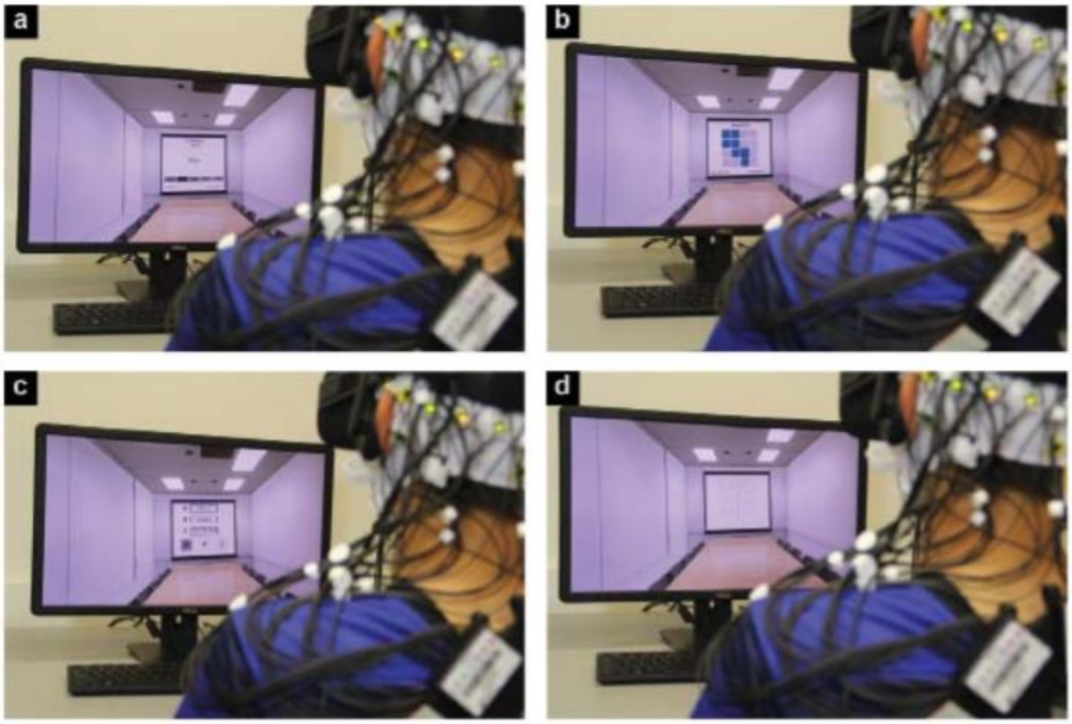


Figure 12: The memory-oriented tasks completed by the participants (a) the Stroop attention test, (b) a spatial memory test, (c) an arithmetic test, and (d) the Benton visual retention test. [27]

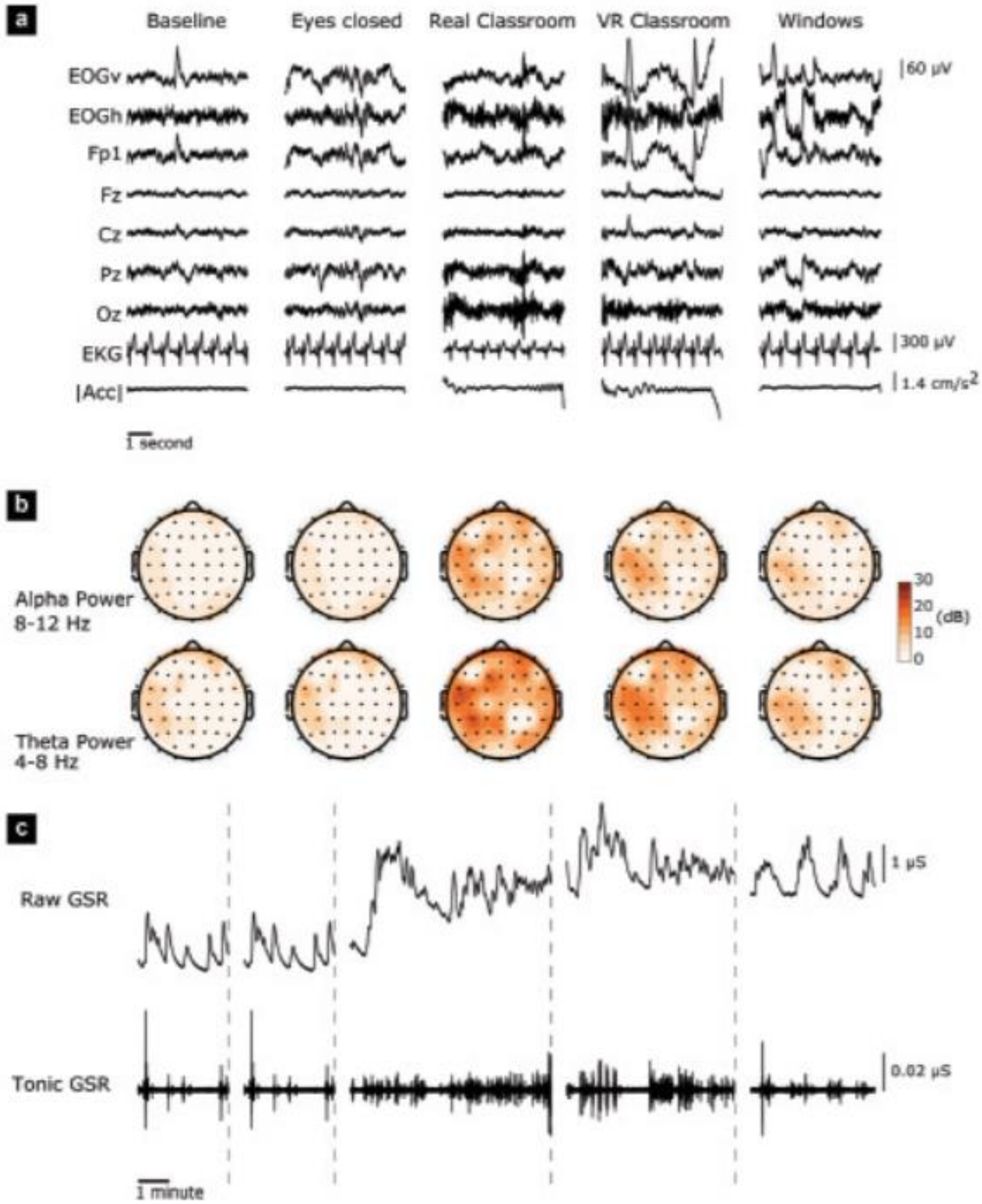


Figure 13: The figure rows show (a) the initial 5s of data from selected EEG, EOG, EKG and head acceleration channels; (b) total alpha (8-12 Hz) and theta (4-8 Hz) power in all EEG channels, and (c) raw and tonic GSR (Skin conductivity) signals. [27]

Navigation & Spatial Cues

Often times when humans land in a new space, they analyze their environment to look for signs or cues that direct them to how to get where they want to be. With any kind of unfamiliar environment or space it requires spatial cues and VR environments are not exempt from this. VR research in cell neurobiology has been done to analyze VR use to support disable individuals in way finding [29]. In this study VR technology was used to help disabled teenagers navigate a supermarket and to asset children navigate schools in wheelchairs [29]. Participants in this study had great success in way finding in these spaces. With the help of VR, it indicates that this technology engages spatial navigation in a realistic fashion. The participants ran through multiple rounds of running through the simulations. The participants were able to learn how to navigate through public places in question [29]. As the participants were placed into the VR environment, they were given navigational cues in the form of markers to guide them through the environment [29]. This has applicability in the SHD field and is useful for spacecraft habitat designers to understand. Creating and developing VR experiences requires attention to ways a user navigates in the environment. If navigation and spatial cues are not well constructed in the environment this could sour the experience. When VR HMDs change the human sight in place of the simulated environment, the boundaries of the design space are replaced. This requires navigational cues and guidance for users inside simulated environments. In terrestrial architecture and design, or a design of any large-scale places are facilitated with signs and navigational cues. The same is needed for SHD, in the International Space Station (ISS) there are navigational cues for crewmembers to guide them through modules and to know what orientation of the spacecraft it is in. Figure 14 and 15 show examples of this. In the same way these cues have to be presented in VR simulation to allow the user to have a positive experience and navigate through the environment successfully.

Figure 14: Example of physical navigational cues on board the ISS [30]

Figure 15: Example of physical navigational cues on board the ISS. [30]

The Importance of Scale, Size, and Reference Points

There is a link between one's perception of themselves and the physical space that they are in. which is why some people tend to feel claustrophobic in small spaces or feel vertiginous in certain perspectives. VR users tend to experience motion sickness which is extremely uncomfortable and can sour the VR experience [32]. Although there is no data or evidence to how that motion sickness is caused by VR. It does not have any long-term side effects [33]. In order to combat VR motion sickness, researchers at Purdue have implemented a virtual nose in VR simulations and found that it helped reduce VR motion sickness by 13.5 percent [34]. Figure 16 depicts an image of what a virtual nose looks like. It has been noted by researchers that the primary reason for motion sickness is sensory conflict [35]. In the Purdue research it was discovered that imprecise scale and body measurements played a crucial role in inducing VR motion sickness. In the same experiment 41 participants used a diverse set of VR applications ranging from the user riding a roller coaster to walking around a Tuscan villa. Half of the participants took part playing games with a virtual nose while the other half played without the virtual nose. It concluded from the study that the participants with the virtual nose were able to play the game for 94.2 seconds longer than the participants without the virtual nose [34].

From this study it can be concluded that having accurate measurements, sale, and body measurements are vital in having a positive VR experience. There is value behind having to experience your design in a virtual environment at a 1:1 scale. It should be noted that when humans have a proprioceptive sense of scale in reference in objective reality [36]. Humans already have an instinctive understanding of their bodily measurement prior entering a virtual environment. With that being said having different reference points from our instinctive ones make users experience VR motion sickness.

This is extremely important when relating this back to SHD, replicating a microgravity environment might induce VR motion sickness because this is completely different from the environment and reference point that we as humans are used to living in. Replicating a microgravity environment in VR is something extremely valuable as it adds in immersiveness and perspective to design conceptualization, this is something that we can’t do with physical models. Figure 17 shows a rendering of alternative perspective of a microgravity environment.

This emphasizes the necessity of reference points, that the VR environment is rendered to scale and that the size of the environment is constraining. Constructing a VR environment to scale, size, and including reference points allows designs to be communicated better to users in the SHD field. Above all, the human perception is a key component to the perception of the environment.

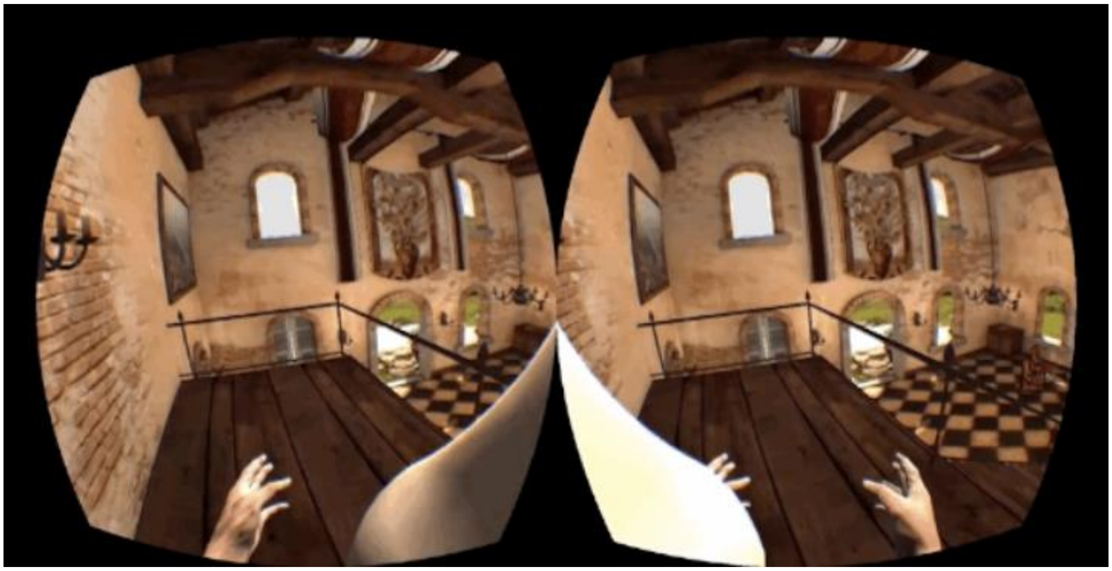


Figure 16: The implementation of a virtual nose to help the user connect to physical reference points [37]

Figure 17: An altering perspective from 1G environment to a Microgravity environment [38]

The Added Value of Narration in VR

Designers wear many caps, one of them being able to educate and communicate their designs to clients and stake holders. In SHD clients and stakeholders only get a chance to walkthrough the design later in the project life cycle phase when physical mockups are constructed. Demonstration of a design typically has a designer escorting the clients and stake holders through the design explaining different areas of the project. Figure 19 shows an example of a walkthrough of a SHD. Translating this knowledge into a virtual experience, a user might not know where to focus in the new environment. An experiment conducted at Oxford University studying alleviating acrophobia found success in the implementation of a virtual coach. In this study participants with acrophobia interacted with different height levels in a VR environment [39]. The experiment places users within a 10-story virtual office building, with guidance of a virtual coach users took on tasks of increasing difficulty. Some of the tasks included rescuing a cat from a tree within the building's atrium, walking along a shaky walkway, and conduct tasks while on the edge of a balcony. Participants were asked from the virtual coach to walk around and activate the hand-controllers during the experiment [39]. The virtual coach was a key component in the experimentation. The virtual coach was an avatar that was programmed with a voice and animation in the VR environment. The virtual coach gave guidance and encouragement to users during their activities which aided in the participants success in the tasks. This demonstrates that any presence in a virtual environment, whether it being a digital avatar or narrational guidance can provide assistance and be beneficial to a user. This experiment exhibits that narration or prompting through audio might be seen as an unimportant feature, when in actuality it can make or break a VR experience. Figure 18 depicts an image of the digital avatar used in the Oxford research. Compelling VR environments often simulate all the senses, but VR currently best stimulates a virtual and auditory experience [23]. There are three ways spatial audio can be transformed in VR they are voiceovers, background audio, and sound effects. Spacecraft habitat designers need to keep in mind the consideration of sound as a real-world experience. From the experiment it shows that sound can be used effectively to guide a user to conduct tasks in the virtual environment. The encouragement that comes from a digital aviator or having narrational guidance can aid a user within the VR environment to focus on their goal. In SHD when designs are being presented physically to an unfamiliar eye, the same auditory guidance is provided by tour guide. The implementation of narrational guidance can extremely be valuable in the design of VR simulations.

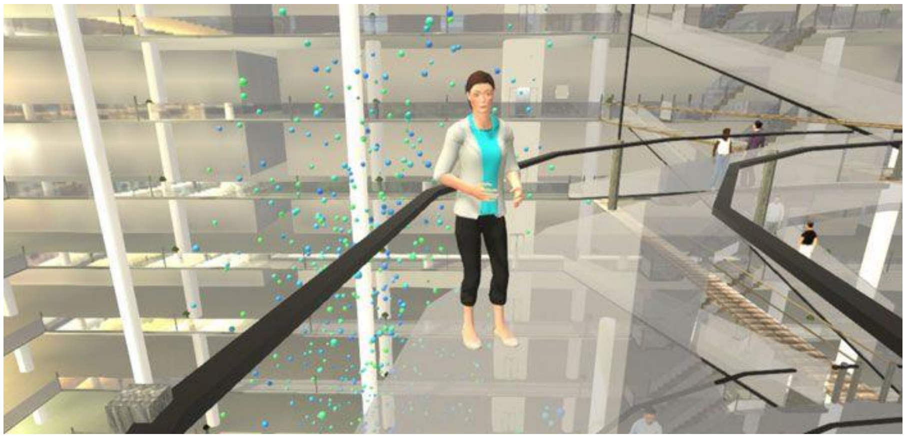


Figure 18: Utilization of digital avatar to guide and assist users [40]

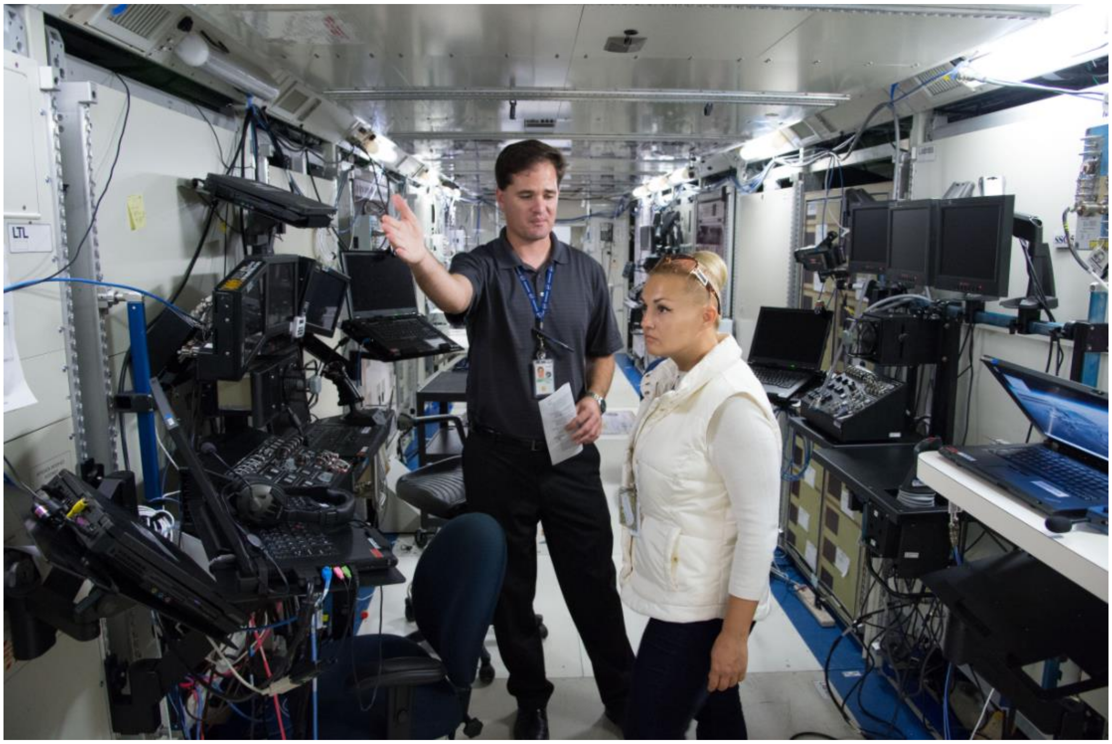


Figure 19: Cosmonaut Elena Serova being given a tour guide of the ISS mockup at NASA Johnson Space Center (JSC) as part of her training [42]

Intuitive Design Interaction

A well-designed spacecraft or habitat can prompt an instinctual physical response. This is also dependent on the function the habitat or spacecraft was designed for. For instance, a habitat made for a lunar surface would encourage walking, sitting in a specific area. While spacecraft design for a microgravity environment would encourage the use of hand railings as the person glides through the spacecraft. While VR is a virtual experience it can still solicit physical responses. An experiment done by Kate Laver demonstrates some of the first breakthrough cases comparing the effects of VR against alternative methods of rehabilitation on participating stroke victims [41]. The experiment aim was focused on the opportunity to recover victims by testing walking speed, the ability to manage daily functions, and testing arm functions following the experience of a traumatic stroke. The experiment studied 72 cases involving 2,470 people after they experienced a stroke. The experiment found that users were able to regain arm function by practicing gait and balance in VR scenarios [41]. The way the VR therapy was designed and conducted in these cases gave the participants the chance to practice everyday activities that were not and could not be created in hospital environment. Figure 20 shows how VR is being used and applied to physical therapy. Granted that the quality of the evidence that was gained in this experiment was low to moderate quality. Fifty of these cases had positive findings that supplementing the use of VR with rehabilitation, or even on its own, resulted in better arm functionality, ability to dress oneself, shower, and better walking ability [41]. The success of using VR to assist rehabilitation shows the tremendous upside that exist with VR technology and its use of interaction. This upside can show promise in SHD, having the ability to shape interactive environments for its inhabitants. Designers should create intuitive spaces allowing users too easily and naturally figure out how to interact with the simulated environment. VR environments without any intuitive design features or elements can cause a user to feel lost, distracted, or unable to focus on the design in question. Intuitive interaction is a crucial component in designing VR environments because it directs actions to the user who is unfamiliarized with this environment. If a user is mean to walk, hang on, attach themselves in objective reality, it would be beneficial to have a simulation of that design space to encourage that. There is current VR research being done on the ISS exploring how microgravity effects astronaut's motion, orientation, and distance perception, Figure 21 displays this.

Psychologist Sally Augustin who focuses on human-centered design further emphasizes this in her work. She believes in the formation of sensory stimuli from physical and virtual environment, she mentions that the design of our environments has great deal of impact on humans [43]. The visualization of lighting effects, textures, renderings, and interactions can have recourse to our innate human sensations. All in all, spatial and visual principles come together to convey that everything makes a difference in the perception of a visual space. Demonstrating a pristine SHD design effectively can be tedious and takes a great deal of thought and effort.

Figure 20: VR is being applied in physical therapy [44]

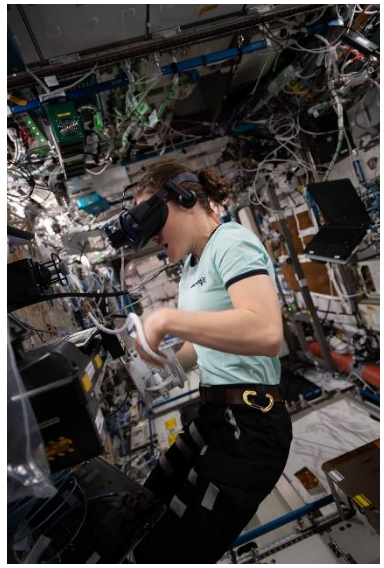


Figure 21: NASA astronaut wearing a VR HMD for the Vection study that is exploring how microgravity affects an astronaut's motion, orientation and distance perception [45]

Practicality of Immersive Representation

University of Waterloo School of Architecture conducted an experiment to see if spatial relationships through VR were accurate [46]. The premise of the experiment was analyzing the difference between determining distances in VR simulations compared to orthographic architectural drawings. This study built a solid understanding of whether VR is an effective tool too use in communicating spatial relationships. The experiment had participant’s approximate distances from an orthographic drawing and move walls in a VR environment to those set distances. Participants were able to move walls closer or farther away from them to affect their perception of the interior space regarding shape, population density, and detail. However, participants were able to have better accuracy with measurements with the drawings, the participants found to create rooms with dimensions similar to one another. This indicates that using VR as representational tool has promise to “impart common understanding of space to different people" [46]. This highly reassuring for designers that VR can be an effective tool to use in design communication. Being able to communicate and represent a design in VR can be linked to phenomenology. Phenomenology can also be understood as the study of structures, experience and consciousness. In terrestrial design phenomenology is the "manipulation of space, material, lights show to create a memorable encounter through an impact on the human senses" [47]. While this relates to terrestrial design, it still correlates to SHD as it still a human centered design discipline. Phenomenology revolves around concepts like spatial awareness and self-conscious through purpose in action. Phenomenology in terrestrial architecture has transferability to SHD, having the ability interact with a design in a virtual environment makes VR attractive in the design field. Architectural scholars like Alberto Perez-Gomez and Steven Holl draw parallel to phenomenology and human perception [48]. They discuss how representational tools influence the conceptual development of projects. Deducing from this evidence it can been from not only a scientific perspective but also from a philosophical point of view that there is use of using VR as a means of immersive representation.

Relevancy Versus Feasibility

This research of this thesis was inspired by the adulation surrounding VR technology in interdisciplinary fields. VR has been displayed as interdisciplinary by VR fanatics and developers in mainstream media. From the successful results of research documented in this chapter one might be easily convinced that VR has a vast array of diverse applicability. Regarding SHD, VR may have a multitude of applications in the practice and design workflow. It doesn’t necessarily assure any feasibility in the practice. Making a good judgment of VR technology will only come from time, effort, and resource it takes to make VR a successful representation to conveying the intent of SHD.

CHAPTER 4: METHODOLOGY

Methodological Proposition

There is a vast array of experiences that can be created within VR and a multitude of ways to go about creating them. The emergence of major VR hardware and software releases in the late 2010s challenged the industry’s VR standards and stimulated a mass production of immersive HMDs. With the recent increase of hardware and software technology for VR, it has made VR technology more accessible both physically and financially. While VR technology has become accessible, the challenge now is selecting and differentiating between hardware and software to create a VR experience. This chapter seeks to address the methodology behind the experimentation in the following chapters and to differentiate between the hardware and software options used within the practice. To address the practicality of VR in SHD, a systematic approach needs to be taken to compare methods and choose the most reasonable method to enable facilitate the experimentation. This chapter will address the methodological approach for experimentation, VR hardware and software, along with semi-structured interviews that were conducted. Figure 22 depicts the components behind the methodology.

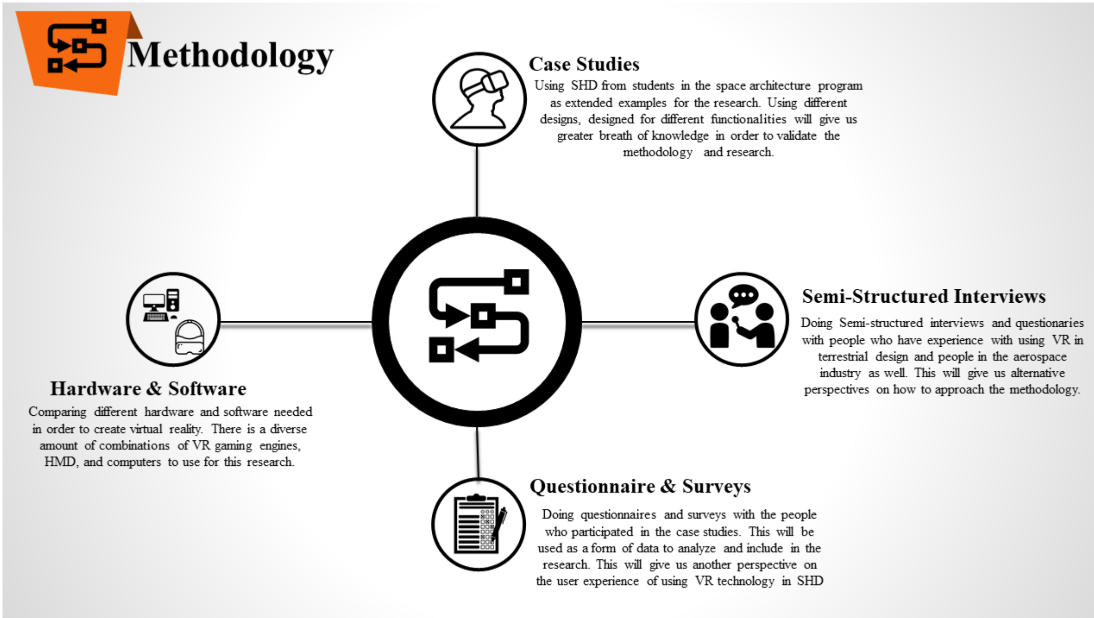


Figure 22: Components behind the methodology

Experimental Framework

Gartner, the world's leading information technology research and advisory company, published an article titled *3 Reasons Why VR and AR are slow to take off*. In the article they mention that the biggest barrier to wide adoption of immersive technologies is the lack of good user experience design [49]. This concern relates to the general understanding of VR practicality in SHD. The user experience of VR has been predominantly tailored too programmers to enhance coding or a gaming background. A gamming approach doesn't necessarily fit within the scope of SHD approach to design creation. In order to access the practicality, spacecraft habitat designer's experience of creating VR experiences must be tested.

To set parameters for the experimentation, this thesis will evaluate VR creation and evaluation from the standpoint of an average design consumer and end user of VR. The study is done in context of research of a graduate student with academic experience in SHD design. Consequently, the standards involve possessing knowledge of 3D modeling software's with having little background of software gaming engines. This research is framed around a student's experience within the human spaceflight profession and is grounded in the NASA project life cycle process rather than within the programming field. To produce a VR experience for SHD standards, this methodology part of thesis is segregated into tasks, one is to evaluate and differentiate hardware and software. After selecting the hardware and software. Experimentation will be done with these hardware and software. The experimentation will be done with two case studies which will be discussed later in the chapter. The results from the experimentation will give the data necessary to set evaluation parameters to evaluate the efficacy and efficiency of VR.

Assessing the ease and accessibility of VR technology requires not only strength in efficiency but also efficacy. There should be no compromise in quality or effectiveness when it comes to designers being able to evaluate their design in VR or to showcase it to clients or peers. Efficiency is integral for designers when it comes to completing tasks to meet a short deadline. It is hypothesized that VR technology is an effective and reliable testing substitute when compared against physical mockup structures. Figure 23 shows the correlation between efficacy and efficiency.

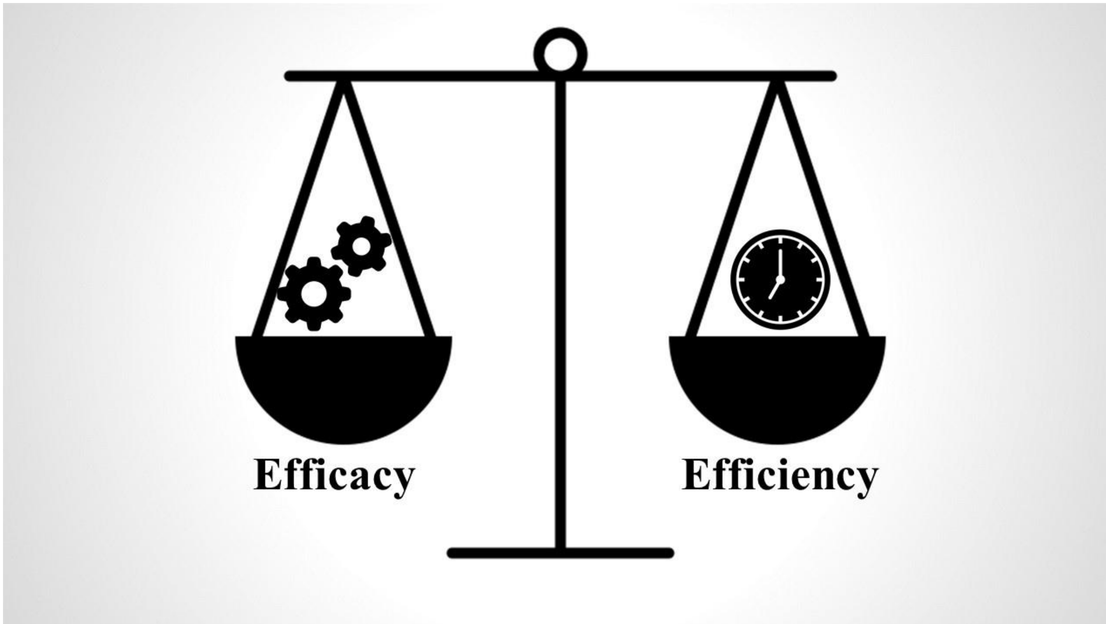


Figure 23: The Judgment of efficacy and efficiency have equal requirements

Semi-Structured Interviews

In order to get a better understanding of how VR technology is being used in today's day and age part of the research methodology is conducting semi-structured interviews with professionals who have experience using VR not only in the human spaceflight industry but as well as terrestrial design. This will give alternative perspectives on how to approach the methodology as well as giving insight on how to integrate VR into the design process. Three professionals were interviewed, a design labs visualization leader at Gensler, a human systems engineer at Johnson Space Center (JSC), and a senior human factors design engineer at JSC. Figure 24 depicts the questions and responses received from these individuals. Gensler is a terrestrial architecture firm; the design labs visualization leader had been using VR and AR for about 12 years. He expressed that they have been using VR/AR religiously in their design process and that it is just as important as the physical mockups they construct. The human systems engineer expressed the interaction with design is something extremely valuable to them with conception of design. The senior human factors design engineer shared that VR has helped them understand relationship of space and human presence. As well as help replicate dynamic operations such as Extravehicular Activity's (EVAs). One of the most notable things from these interviews is that all three expressed the same problems and limitation of VR technology. All expressed that the biggest limitation and problem with VR technology is the usability aspect of it. Things such as the HMDs being too bulky and not very user friendly and the time it takes for users to get acclimated to the VR environment. This will continue to be a hurdle for designers and end users till VR technology become more and more user friendly and intuitive. Being that it is consumer driven and the progress it has made over the past decades. The technology will become easier and easier to use to allow for better experiences for users and designers.

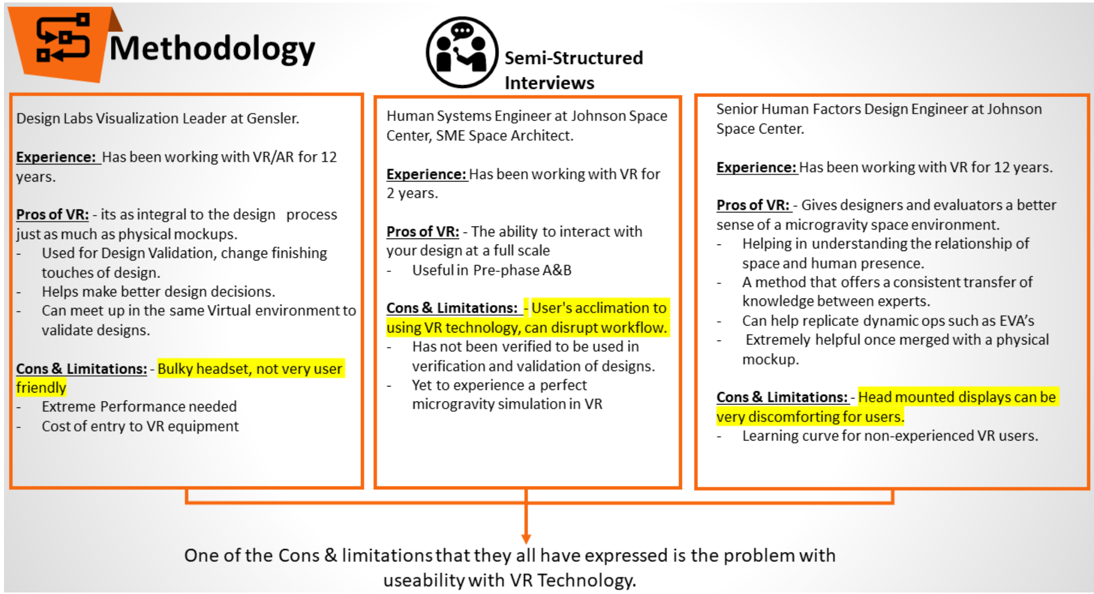


Figure 24: Each interviewer was asked their experience with VR, pros, cons and limitation with using VR technology

Distinguishing and Comparing VR Hardware

In the consumer realm of VR technology, HMD are split into three different categories; VR smartphone, tethered, and mobile. Most VR smartphone HMDs are headsets with a shell and lenses into which a smartphone is placed in. The cons of VR smartphone HMD are that they are limited in immersion experience compared to tether HMD and mobile HMD displays. There is physical limitation to these VR smartphone HMDs, the user is primarily stationary in this experience. First generation VR smartphone headsets allow for exclusively stationary experiences. Gyroscopic sensors and accelerometers are present in the mobile devices sense head rotation. This allows a user to look around for their stationary VR experience. VR smartphone HMDs are dependent on the phones battery capacity and it could easily drain the phones battery. The upside of these VR smartphone HMDs is that they are easy to use and accessible to a smartphone, and an affordable introduction to VR. Some examples of these VR smartphone HMDs include Google Cardboard, Google Daydream, and Samsung Gear VR Cite [50].

The other type of HMD is tethered HMD, which allow the user to move their head and walk around at the same time, additional external sensors are video processers are required to track the physical position of the user. VR experiences were the HMD track the physical position along with head rotation are commonly referred to as room-scale VR experiences. Tethered room scale experiences help facilitate room-scale experiences, they come with built in motion sensors and external hardware in form of camera trackers to allow for complex and immersive VR experiences. Examples of these HMD are the HTC Vive and Oculus Rift, they connect to a personal computer which can take all the computational load of video processing into the PC itself [50]. Tethered HMD offers more promise in respect to assessing applicability in SHD. Tethered HMD allows a user to freely walk around in the VR environment, translating physical movement from reality into their digital environment. The cameras monitor a user’s environment in 3D space, this allows for greater immersion for the user with digital translation. Walking across a design space digitally is equated to walking around a physical room, this simple factor can provide another layer of design perspective for SHD visualizations. At some point in the project life cycle spacecraft habitat designers must construct and show case the project in life like scale. While this is done with physical mockups, it takes a tremendous amount of money, time and resources to do so. Tethered HMD can allow SHD to experience their designs in life like scale early in the design process, this becomes a necessary additional factor of implementation. Lastly are mobile HMD where they no longer need to be tethered to a computer. The upside of these HMD is the user can walk freely without being restricted by the tethered. They have built in video processing systems, sensors, and cameras. The downside is that they don't have the same computational capacity as a regular computer. With companies like Oculus and HTC offer the tether with these kinds of HMDs to hook up to the computer to access the computational power of your computer. Some examples of these mobile HMD are Oculus quest 2, and HTC Vive Cosmos Elite. Tables 3-5 show the different type of HMDs in each category, and the specs that come alone with them. Figure 26 depicts a Venn diagram distinguishing the categories of HMDs. Fig 25 illustrates the leading companies producing VR HMDs.

Table 3: VR Smartphone HMDs Specs

VR smartphone HMDs	**Google Cardboard**	**Samsung Gear VR**	**Google Daydream**
Price US Dollar (2021)	$15.00	$130.00	$70.00
Platform	Android	Android	Android
Experience	Stationary	Stationary	Stationary
Resolution	Dependent on Smartphone	Dependent on smartphone	Dependent on smartphone
Field of View	Varies	101 degrees	90 degrees
Headset weight	0.57 lbs without phone	0.76 lbs without phone	1.2 lbs without phone
Refresh rate	60 hz or above dependent on smartphone	60 hz or above dependent on the smartphone	60 hz or above dependent on the smartphone
Controllers	Single headset button	Single headset button, single motion controller	Single motion controller

Table 4: Tethered VR HMDs

Tethered VR HMDs	Oculus Rift S	HTC Vive Cosmos	PlayStation VR	HP Reverb 2
Price US Dollar (2021)	$599.00	$699.00	$349.00	$549.00
Platform	Windows, Mac	Windows, Mac	PlayStation 4, PlayStation 5	Windows
Experience	Stationary, Room-Scale	Stationary, Room-Scale	Stationary	Stationary, Room-Scale
Resolution	2880 x 1700	2880 x 1700	4000 x 2040	4320 x 2160
Field of View	110 degrees	110 degrees	110 degrees	114 degrees
Headset weight	1.1 lbs	1.5 lbs	1.3 pounds	1.2 lbs
Refresh rate	90 hz	90 hz	90 hz	90 hz
Controllers	Dual motion controllers	Dual motion controllers	Dual motion controllers	Dual motion controllers

Table 5: Mobile VR HMDs

Mobile VR HMDs	Oculus Quest 2	HTC Vive Cosmos Elite
Price US Dollar (2021)	$299.00	$899.00
Platform	Windows, Mac	Windows, Mac
Experience	Stationary, Room-Scale	Stationary, Room-Scale
Resolution	2880 x 1700	2880 x 1700
Field of View	110 degrees	110 degrees
Headset weight	1.1 lbs	1.5 lbs
Refresh rate	90 hz	90 hz
Controllers	Dual motion controllers	Dual motion controllers

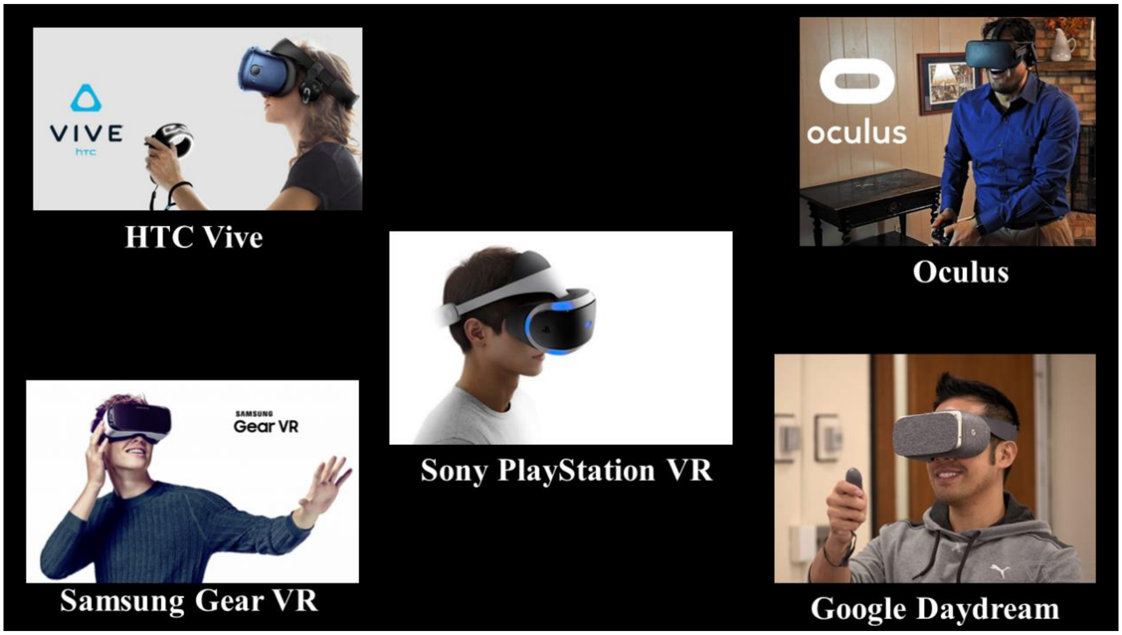


Figure 25: Leading Companies in VR HMDs

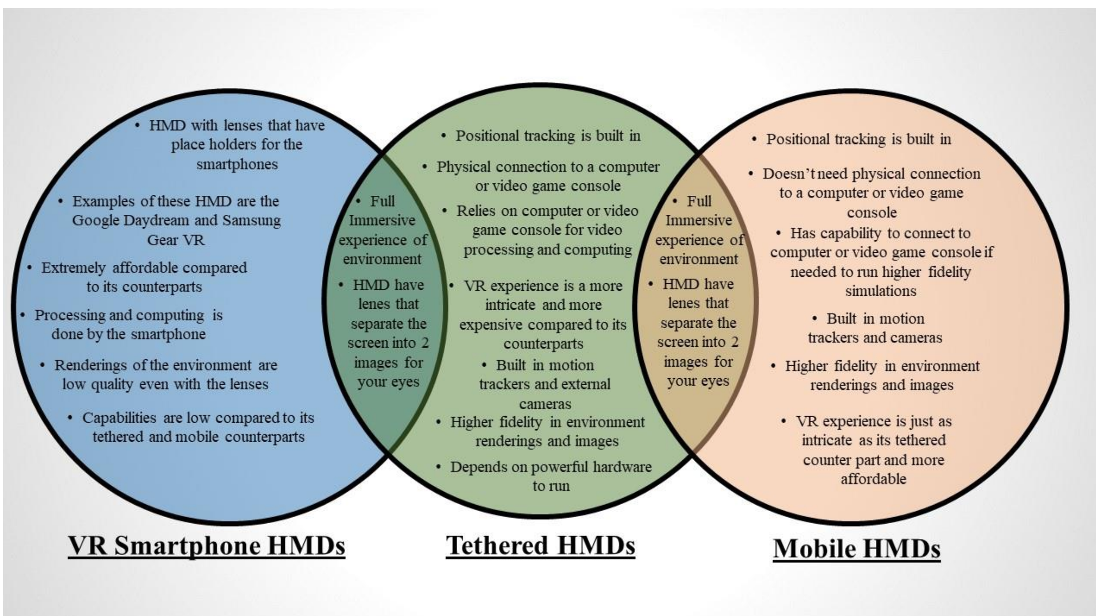


Figure 26: Venn diagram distinguishing the HMDs

The Oculus Quest 2 and HTC Vive Cosmos Elite represent the higher end of VR experiences available at the time of writing. These HMDs are dexterous being that you can switch from it being mobile or tethered. The above mentioned HMDs are also well-tested consumer-based headsets. Between the higher-end devices, the Oculus Quest 2 was selected as the device used for this thesis given its greater consumer base.

Layers of Immersions with Different Hardware Options

The scope of this thesis primarily focuses on the use of entry level and high-end consumer VR hardware, to examine the range of hardware options available to spacecraft habitat designers. With advanced hardware currently used in the laboratory setting is an important consideration for future research done within this topic. Once advanced VR technology reaches a point in SHD where it is being used religiously in the design process, then experimentation with more advanced hardware would be worthwhile to recreate. At the time of this writing VR has been shown to successfully manipulate the human visual sense into seeing a different environment than the one physically inhabited [51]. However, there are other elements that contribute to the illusion of being teleported into another location. Entry-level VR hardware all activate rotational head tracking. This permits the user to interact with the environment through their sight. High-end consumer VR add another layer of immersion by the use of sensors and controllers that enables positional tracking. Positional tracking is what lets the user to interact with the virtual environment and employs human proprioceptive cues. This is typically achieved with the use of binaural audio, which allows a user to hear sound naturally as it spatialized. The final layer of immersion that advanced VR hardware gives is by allowing for sensorial tracking and haptic feedback. These feature aid in stimulating other human senses in the way of vibrations and temperature changes both the user and object. VR currently gives sense of sight, sound, and touch with each level of immersion. VR has had trouble in recreating the human sensation of smell and taste. The most natural and comfortable VR solutions currently are advanced VR options, these options are extremely expensive and labor intensive to implement. Some of these implementations include full haptic suits [52], “warehouse-scale” experiences with backpack computers [53] and omnidirectional treadmill [54] all of which allow a user to freely walk within their environment and experience the added sensations of their environment. The higher level of immersion that advanced hardware can provide is an important consideration from the perspective of a designer. Although these implementations are often expensive and difficult to physically recreate, and there are questions around the applications to these hardware’s in SHD. The scope of thesis focuses on entry level and higher consumer levels of immersion with VR hardware, rather than advanced VR options to justify practicality within the SHD field.

VR Gaming Engine Software’s: 3D Modeling Creation and VR Scene Creation

The design process of any large complex engineering system has undergone transformation due to the emergence of computer-aided design tools. In today’s day and age, any conceptual phase is based on iterative 3D model-making which then derives 2D manifestations of the design typically in the form of plans and sections of the design [55]. VR gives the capability for designers and clients by improving the communication of their ideas. If a 3D viewable model can be easily transported into a

4-dimensional (4D) scene for VR viewing, it enhances the designer and clients understanding of the unbuilt environment by allowing them to interact with in a more realistic way. Without having to envision the design just from orbiting around a 3D model on a computer screen. If the most common computer-aided design tools can export a model and having it be able to be imported into a game engine for VR scene creation to create simple walkthroughs, validate design requirements, and design constraints. The design process could reap the benefits of this tremendous value in using VR as part of the SHD process.

The experimentation of this thesis will therefore focus on converting 3D SHD models into 4D experiential content for people to examine. For the basic consumer, VR is as simple turning on their Oculus Quest 2 and staring up an application for a game they already have downloaded from on the Oculus store. For spacecraft habitat designers, VR will indefinitely be more complex that. Due to that fact that each project will need its own applications, needs, and objectives.

Starting with a SHD model built by any common 3D modeling software (such as SolidWorks, AutoCAD, 3dsMax, Blender, Rhino 3D) and passing the model into a gaming engine where VR experiences will be built. Figure 27 shows the workflow of creating a VR experience. VR experiences are primarily developed on gaming engines, such as Unreal Engine, Amazon Lumberyard, CryENGINE, Unity 3D, and Twinmotion. Table 6 differentiates all the gaming engines and their specs related to them. The primary gaming engines that will be focused on for experimentation are Unity 3D and Twinmotion. Any project created on any 3D modeling software will have to be exported, pass through an intermediary to convert textures and material properties and then important into Unity 3D and Twin motion for scene creation and deployment onto one's own specific hardware. By exploring SHD projects exports into game engines, the practicality of VR content creation in the SHD field will be evaluated throughout this thesis.

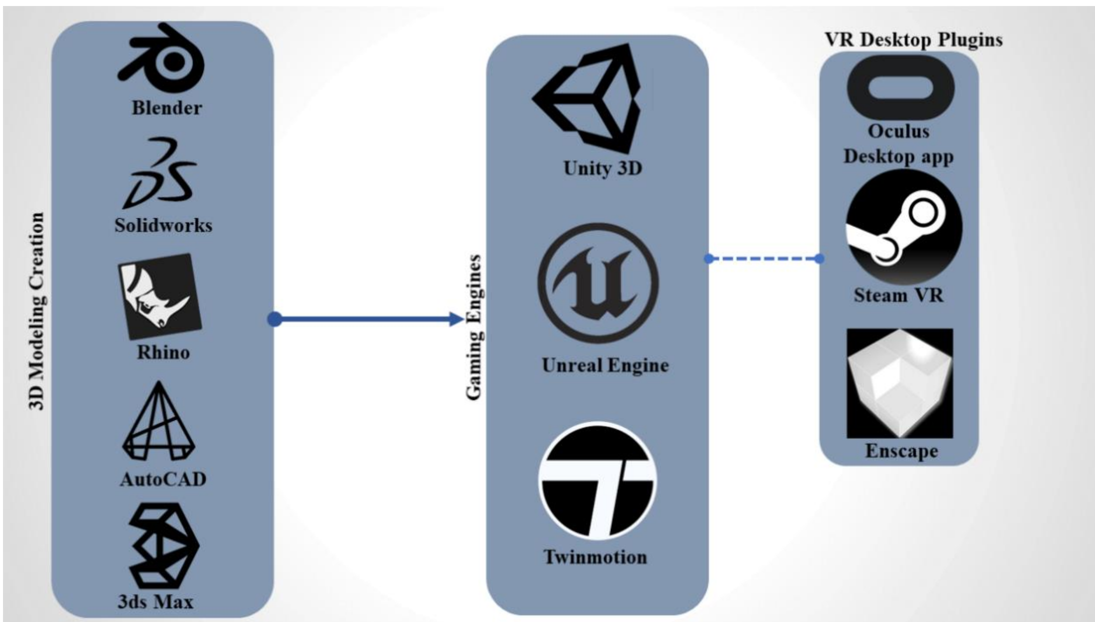


Figure 27: VR creation workflow from 3D modeling to VR experiences

Table 6: Differentiating between game engines

	Unreal Engine 4	**Unity 3D**	**CryENGINE**	**Amazon Lumberyard**	**TwinMotion**
Entry Level	Medium	High	Very High	Very High	Low
Language	C++	C#, JavaScrpit	C++	C++, Lua	N/A
Community	Large	Large	Small	Medium	Small
Computer Requirements	Medium	Medium	High	High	High
Cost	No	No	No	No	No
Graphic Quality	Very High	Medium	Very High	Very High	Very High
2D/3D Object Creation	Both	Both	Both	3D only	Both

VR Simulation Creation Approach

VR's primary purpose is to attract the user's attention to the screen before their eyes. This might seem obvious and intuitive but it's much easier said than done. Users still have freedom of choice too look at whatever they want in a VR Simulation. With adding certain features like narration, guide, or storytelling will help draw the user's attention to initiate specific actions or focus their attention to specific aspects of the VR simulation. Content creators have noted certain features that help users stay engaged in the VR simulation. Some of these features being narration, audio cues, and differentiating the lighting between objects to tell the difference of what's important and what's not. There is a common rule when displaying objects in a VR simulation, there is a maximum, minimal and optimal distances for objects. This is correlated to the theory that when objects are closer to human eye it begins to strain to focus. Oculus developers recommend a minimum distance of viewable objects to be placed at 0.75 meters to prevent eye strain, the effects of which fade considerably between 10 and 20 meters. A more comfortable range of motion for user to rotate their head vertically and horizontally is between 30 and 55 degrees [50]. Figure 28 displays the viewing distances and affordances needed for a user in a VR simulation.

Following this rule of thumb of viewing distances will be able to provide proper feedback from the user and help them navigate through the VR simulation as intended. With VR being a highly engaging experience, the user needs to be directed to pay attention to the important things. There are also common guidelines for what should not be done in a VR simulation. As discussed, earlier VR motion sickness is something that can sour a user experience. To combat this, any application must sustain a frame rate of 60 fps or higher and avoid acceleration/deceleration [56].

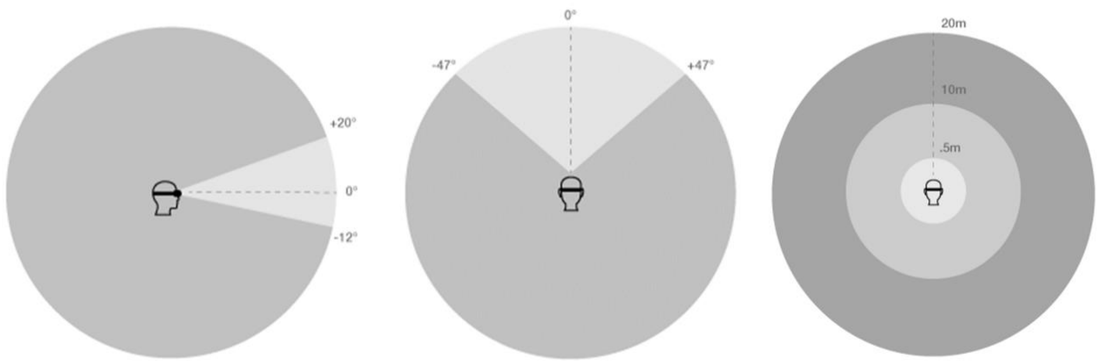


Figure 28: Viewing distances for users in a VR simulation [56]

Case Studies

The case studies used in this thesis are SHDs from students at Sasakawa International Center for Space Architecture (SICSA) at the University of Houston. For the research to be more demonstrative, selecting SHDs designed of different functionalities will give a greater breath of knowledge in order to validate the methodology and research. Two SHD were selected to be used as case studies, one being the Ceres Exploration Vehicle (CEV) design. The other being a Small Lunar Habitat design. The CEV was a design project for a human mission to Ceres concept where the spacecraft would descend down to the surface of Ceres supporting a crew of two for 3-6 days. A rendered design overview of the CEV is seen in Figure 29. The internal architecture and external features of the CEV are shown in Figure 30 and 31

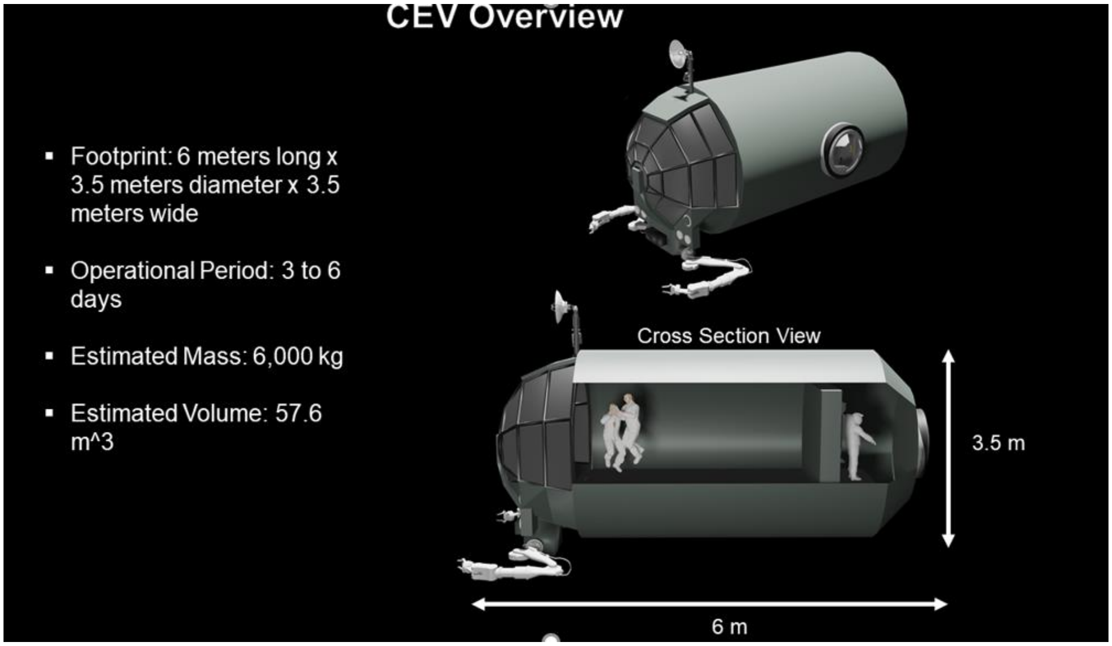


Figure 29: Rendered design overview of the CEV

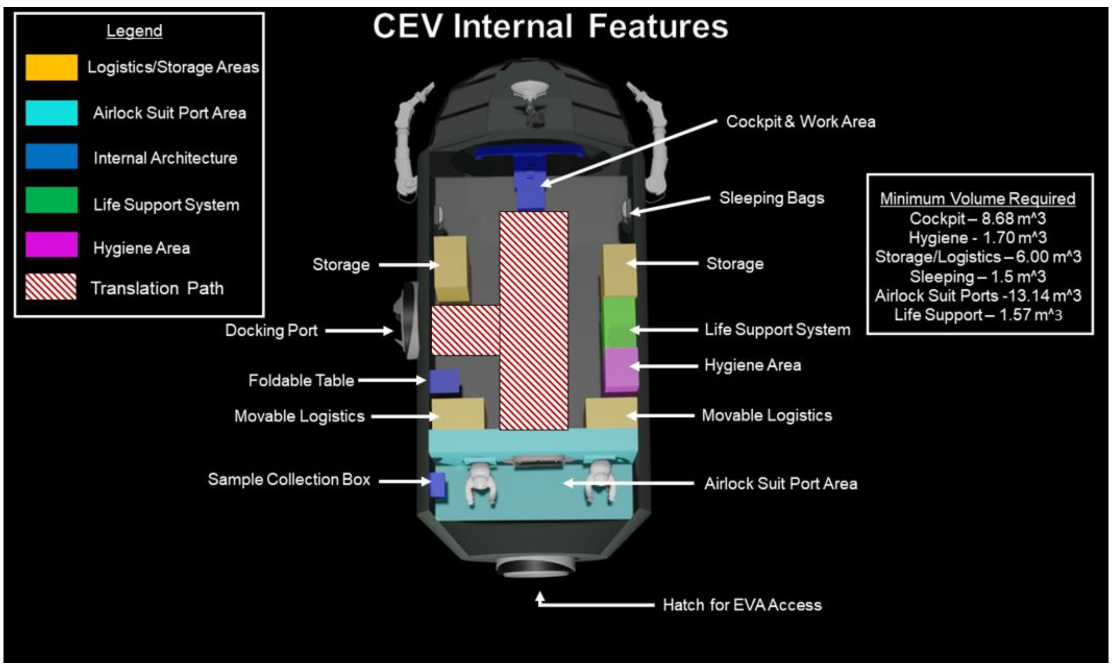


Figure 30: CEV internal architecture

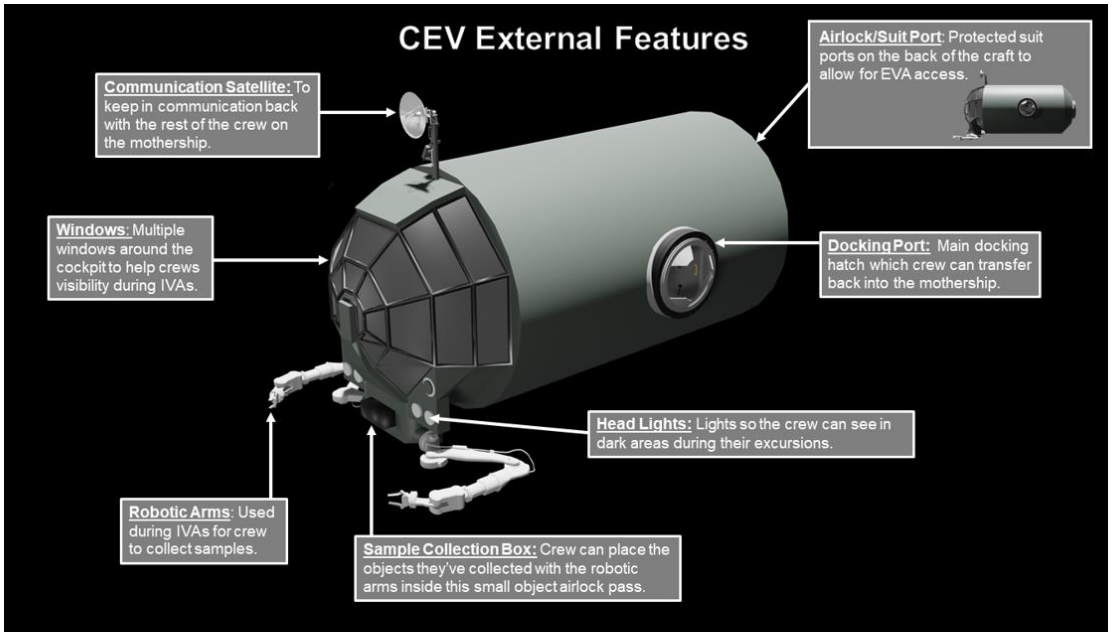


Figure 31: CEV external features

The Small Lunar Habitat was a design project for a lunar habitat concept for the Artemis program. The design was intended to support a crew of four for 14 days on the lunar surface. A rendered design over of the small lunar habitat is shown in Figure 32. Figure 33 depicts the internal architecture of the design, and Figure 34 is a cross section view. Having one design that was intended for a microgravity environment and the other being a partial gravity gives a vast array of variables to investigate. It is hypothesized that VR technology might not be effective and efficient to use for all SHDs. Microgravity environments are extremely hard to replicate in VR. Even when replicated, the immersiveness and presences are not truly there because on Earth the user is still in a 1G environment. So, the user still maintains the feeling of being on earth and not truly being in a microgravity environment. This can cause virtual motion sickness as well, since the user is experiencing a whole different way of movement in the VR simulation compared to how the users moves in objective reality.

Replication of a microgravity environment in VR could be extremely tedious and could serve problems to the end user experiencing it. If the users experience is obstructed from virtual motion sickness or lack of immersiveness then it becomes less conducive and effective to use. Partial gravity designs like the Small Lunar Habitat could be receptive and effective to use VR technology for design validation and verification being that it’s more analogous to terrestrial design. In order to validate this hypothesis these case studies will be used as extended examples for experimentation for this thesis. Both case studies were 3D modeled and designed in Blender and will be exported into various gaming engines for VR experience creation. The CEV design will be imported to Unity and the Small Lunar Habitat will imported into Twinmotion. The reasoning behind placing each case study in different gaming engines is to explore the limitation and upsides of each gaming engine. Doing this will give an expansive approach to the methodology and investigation. After creating the VR simulations, they will be experimented on with participants conducting walkthroughs and interactions with design. There will be certain evaluation objects that participants need to complete throughout their VR experience. After the participants complete the VR experience, they will complete an exit survey regarding their experience. The answers collected from the exit survey will be used as data to analyze and make conclusions from. The exit survey will be discussed later in the chapter and chapter five will go into depth of the experimentation.

Figure 32: Rendered design overview of the Small Lunar Habitat [57]

Figure 33: Small Lunar Habitat internal architecture [57]

Figure 34: Small Lunar Habitat cross section [57]

Questionnaire & Exit Survey

A key step in the methodology is the questionnaire and exit survey. Before entering the VR simulation participants will fill out a questionnaire. The questionnaire includes demographic and experience related questions. There are a few key questions in the questionnaire, which will play a big role in helping to deduce answers to the research questions. Could it be that people with prior experience with using VR technology have less of a learning curve in whatever VR simulation they are placed in? Whether it being recreational experience with it or professional work experience with it. The other key question is regarding the background or profession of the participant, do people with a technical background have less of a learning curve when using VR technology? Or could the opposite be true that even a person with no technical expertise or background could find using VR technology very intuitive. The answers collected from these questions will be the data needed to analyze and answer the research question regarding the efficiency and efficacy of VR technology.

These questions are pertinent when relating it back to SHD. SHD is a multidisciplinary field, not everyone in a design project comes from a hard sciences background. The other fact to consider is that not everyone in a design project may not have expertise or experience with using VR technology. If VR technology has an extremely steep learning curve then this could disrupt workflow, this could even further complicate the design process and increase time and money in the design project. This is opposite of what NASA intends with their paradigm shift as discussed earlier. If VR technology has a small learning curve and is intuitive to the end user then could serve sufficient for everyone working in the design project.

The exit survey will be taken after the participants have finished the VR simulations of the SHDs. The purpose of the exit survey is to gather answers to questions that relate to the SHD VR simulations. The answers obtained from the exit survey will then be used as data to draw conclusions and answers to the research questions. The exit survey will build the base for the evaluation criteria for VR technology. There are four subgroups within the exit survey, embodiment, locomotion, situational awareness, and usability. Figure 35 depicts the type of questions related to each subgroup. As discussed earlier the importance of embodiment and that it is a combination of scale and presence. The embodiment subgroup questions will revolve around certain dimensions of the SHD, immersiveness of the VR simulation, and interactivity within the simulation. Embodiment is an important aspect to consider when judging the efficiency and efficacy of VR technology.

Next is locomotion, these questions will revolve around the mobility within the VR simulation and the objective reality. If users can't move efficiently within both then this can sour an experience and could serve ineffective for spacecraft habitat designers. The other subgroup is situational awareness, where participants will be asked if they noticed certain objects within the VR simulation. As discussed earlier when creating a VR simulation there are certain guidelines to follow when placing certain objects within the simulation. This will be important gauge VR technology's ability to help display certain aspects of design to the end user.

Lastly is usability, the usability subgroup questions will revolve around the participant's access to evaluation tools within the simulation and the evaluation objective tasks. The evaluation objective tasks will be later explained in chapter five. If participants can access all the evaluation tools and complete all the evaluation objectives without any difficulty, then it would show the usability aspect of VR technology could be trusted. On the other hand, if the opposite is true and participants are unable to access the evaluation tools and unable to finish the evaluation objectives then this could cause some concern on the usability of VR technology. Once all the data is collected it will be analyzed and these four subgroups will be the evaluation criteria used to evaluate the efficiency and efficacy of VR technology for SHD.

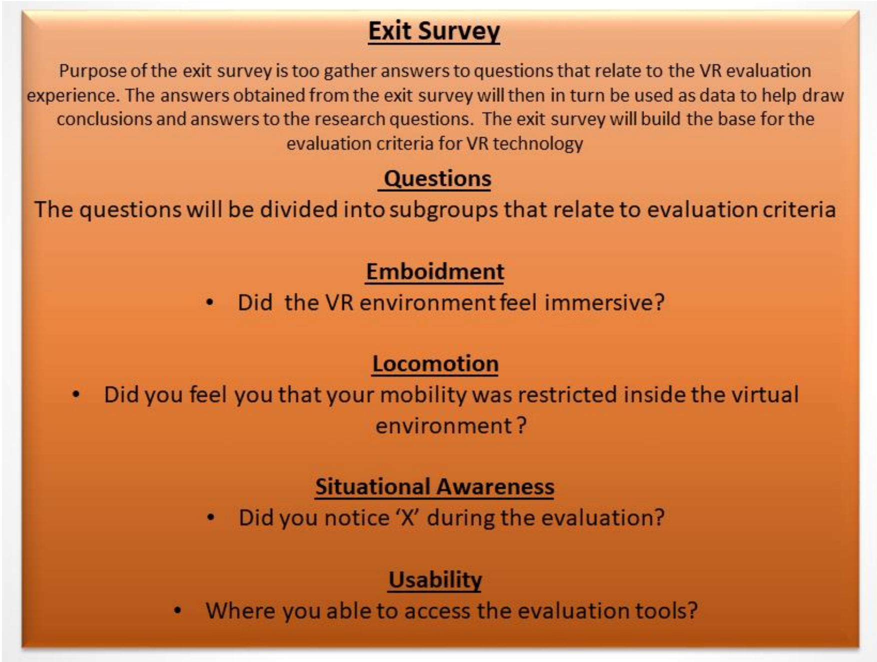


Figure 35: Exit survey subgroups and examples of questions

CHAPTER 5: EXPERIMENTATION

Participants

A total of 31 participants of varying backgrounds conducted SHD VR simulations. Five of the participants had a technical professional background, the other 26 participants did not and were students from the University of Houston. Each participant went through both VR simulations of the CEV design and the Small Lunar Habitat. Prior to doing the experiment all participants were give familiarization training on the functions of the VR systems, as well as how to move and operate inside the VR simulation. They were also briefed on the evaluations and tasks expected of them in each simulation. With all of these tasks combined, each session with a participant lasted an hour on average. The whole experimentation process is shown in Figure 36. The experimentation took place in SICSA's VR laboratory at the University of Houston. The dimensions of the VR laboratory are 22 feet by 20 feet. Figure 37 shows a picture of the laboratory space.

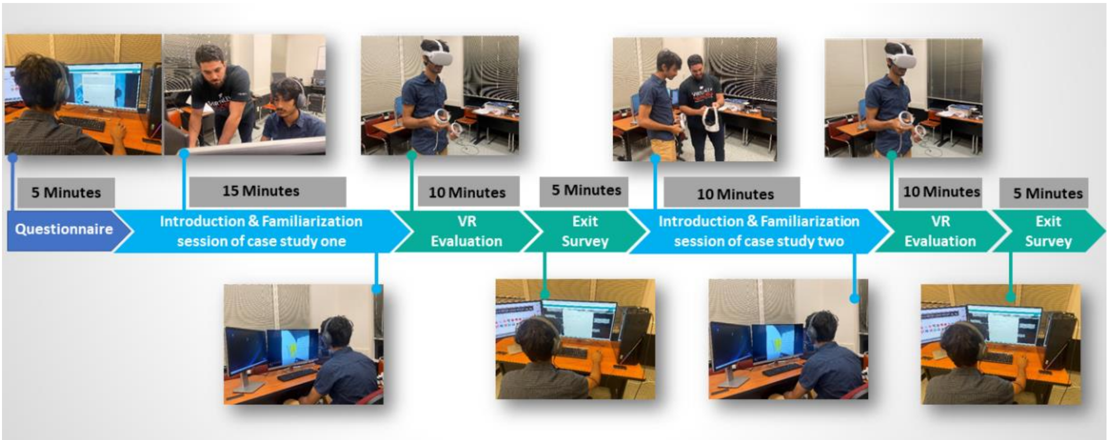


Figure 36: Experimentation Process

Figure 37: Photo of the VR environment in SICSAs VR laboratory with the VR simulation.

VR Simulation Evaluation Objectives and Tasks

In each VR simulation participants were asked to complete certain evaluation objectives in each VR simulation. Each VR simulation for the most part had the same evaluation objectives. The CEV VR simulation was able to conduct more evaluation objectives due to the gaming engine being used to facilitate the VR simulation. The CEV was considered a low fidelity design, and the Small Lunar Habitat design was considered a high-fidelity design. Both designs were not fully functional, meaning they were not operational inside the VR simulation. For example, users inside the VR simulation couldn’t operate the CEV and traverse along the surface of Ceres. On the same hand users in the Small Lunar habitat design couldn't operate the airlock etc. Thus, a walk-through type human in the loop evaluation objectives were performed to conduct visual inspections, immersiveness, and scaling of the design. Table 7 and 8 shows the evaluation objectives and tasks for each VR simulation.

Table 7: CEV VR simulation evaluation objectives

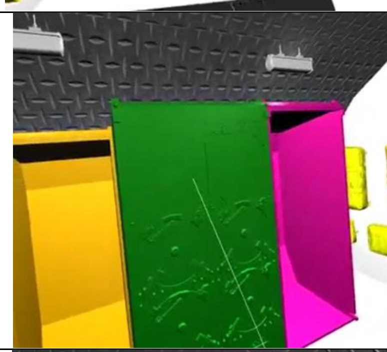
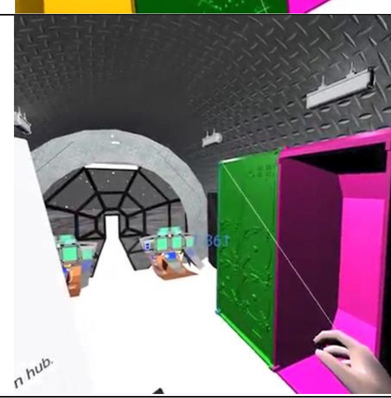
Evaluation Objective	Inside The VR Simulation
Pull up floor plan of the spacecraft	
Locate the life support rack	
Measure life support rack	

Table 7 continued

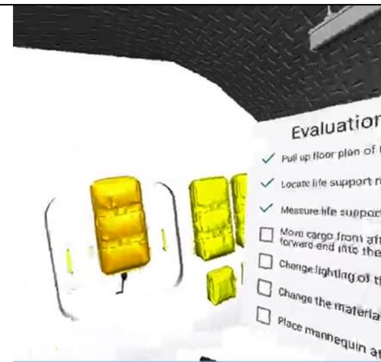
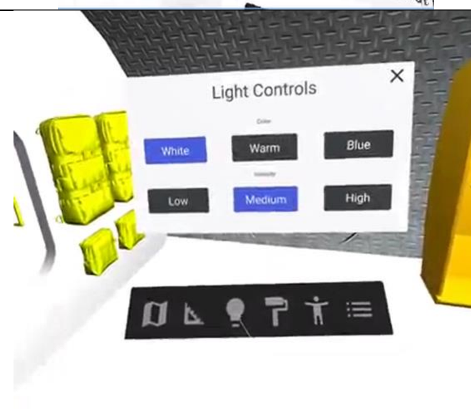
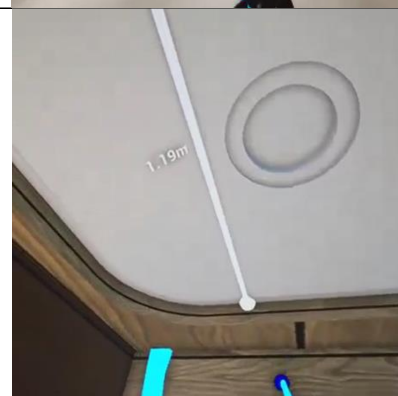
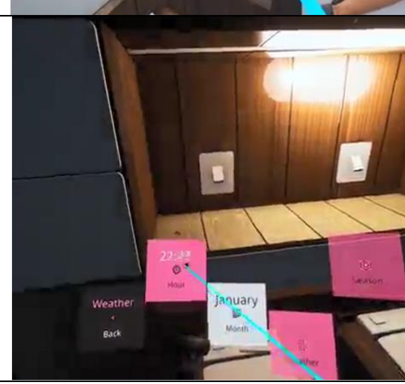
Move cargo from aft end of the vehicle to the forward end into the storage areas	
Change the lighting of the vehicle	
Change the material of the spacecraft	
Place the mannequin at the command center	

Table 8: Small Lunar Habitat VR simulation evaluation objectives

Evaluation Objective	Inside The VR simulation
Use the presenter tool to teleport into different places in the design	
Examine the measurement inside the crew quarters	
Change the material of the habitat	
Change the lighting of the habitat	

Procedures for the experiment were as follows. The participant first fills out the demographic questionnaire then followed up with introduction and familiarization session as shown in Figures 38 and 39. In the first introduction and familiarization session the participant will watch a video covering the overall purpose of the research, the purpose behind the CEV design, and how to move around in the VR simulation and use the evaluations tools in the VR simulation. Afterwards the participant will be briefed on how to put on the HMD and controllers. The participant will then begin the first VR simulation of the CEV design. Once they have completed the first VR simulation the participant will then take the first exit survey as shown in figure 40. After that the participant will do another introduction & familiarization session on the next VR simulation of the Small Lunar Habitat. Where they will watch a video on the purpose behind the design and how to move around in the VR simulation and use the evaluation tools in the virtual space. Finally, the participant will take the last exit survey. Participants were also timed during each VR simulation they were in; this will be used later for data and analysis.

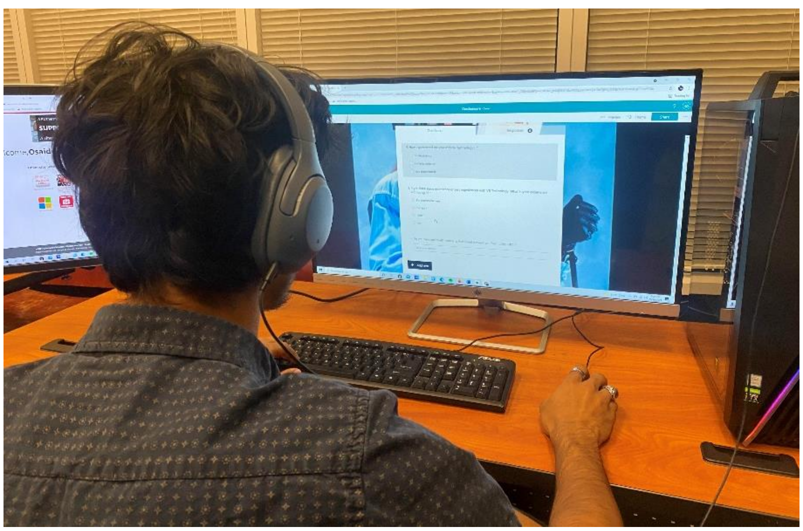


Figure 38: Participant taking the demographic questionnaire

Figure 39: Participant watching tutorial video on how to navigate around in the VR simulation (top). Participant being showed how to wear the HMD and how to use the controllers (bottom).

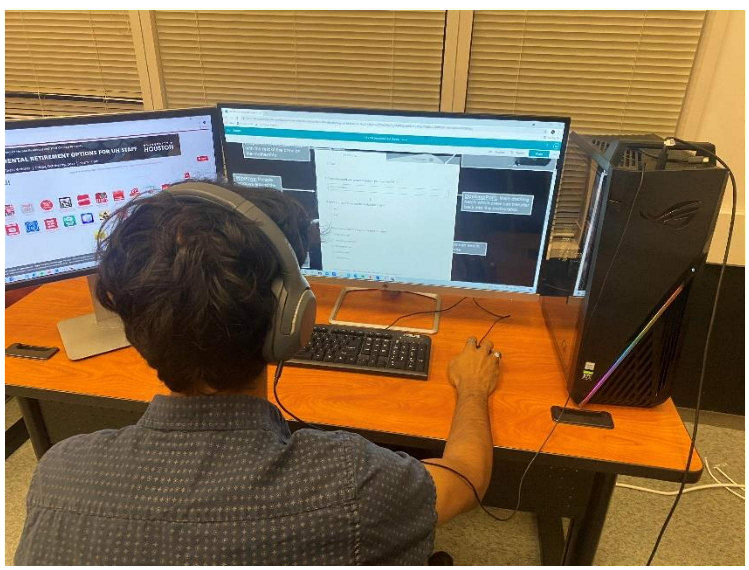


Figure 40: Participant taking the exit survey of the CEV VR simulation

CHAPTER 6: RESULTS AND DISCUSSIONS

A demographic analysis was used to show the age, gender, experience with VR technology, and profession or background participants had. A two-sample t-test between the two VR simulations using the data obtained from the exit survey was employed to evaluate embodiment, locomotion, situational awareness, and usability between the CEV VR simulation and Small Lunar Habitat VR simulation. The null hypothesis is that there is no difference between the two case studies, and both will result in the same outcome in relation to evaluation criteria. The alternative hypothesis is that each VR simulation will produce different outcomes in relation to the evaluation criteria and that both case studies are not equal. In doing the two-sample t-test the smaller the p-value that is produced, the more surprised one would be by the observed difference in sample. Therefore, the smaller the p-value, the stronger the evidence that the two cases have differences, and one would have to reject the null hypothesis and accept the alternative. Figure 41 further explains the differences between the null and alternative hypothesis.

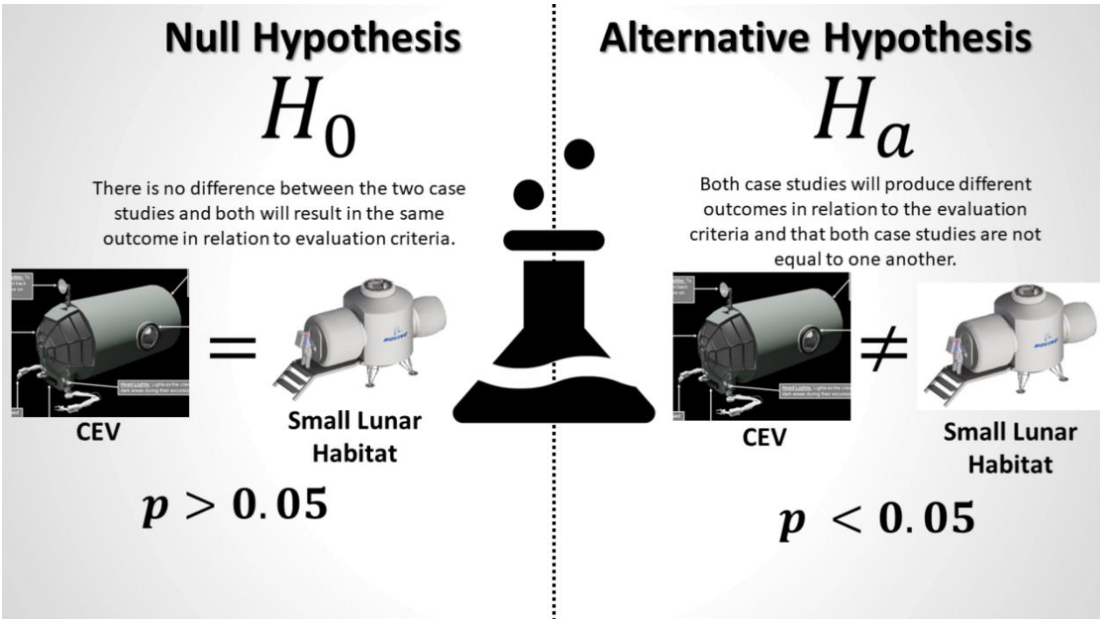


Figure 41: Differences between the null and alternative hypothesis for both VR simulation case studies

Demographic Analysis

A total of 31 participants were selected to participate in the experiment. Of the 31 participants five had a technical profession background, the other 26 had backgrounds of being students at the University of Houston. 22 of the participants were male and nine were female. 25 of them were from the range of 18-25 years old, five of them were from the range of 25-35 years old. One person from the range of 55 years and above. With regards to the experience the participants had with VR technology, 11 had no experience using VR technology. 17 had some experience and three we very experienced. The participants who said they had some experience or very experience VR technology were asked what their experience was with using it. Figures 41 and 42 illustrate the demographic classification.

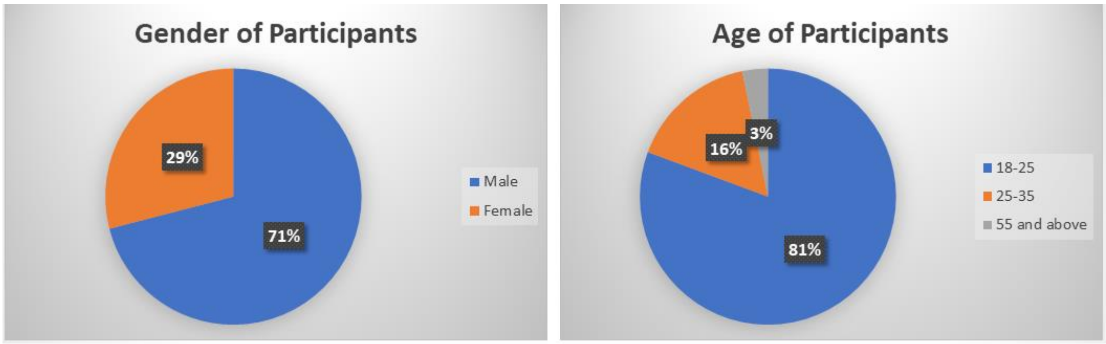


Figure 42: Gender and age of the participants

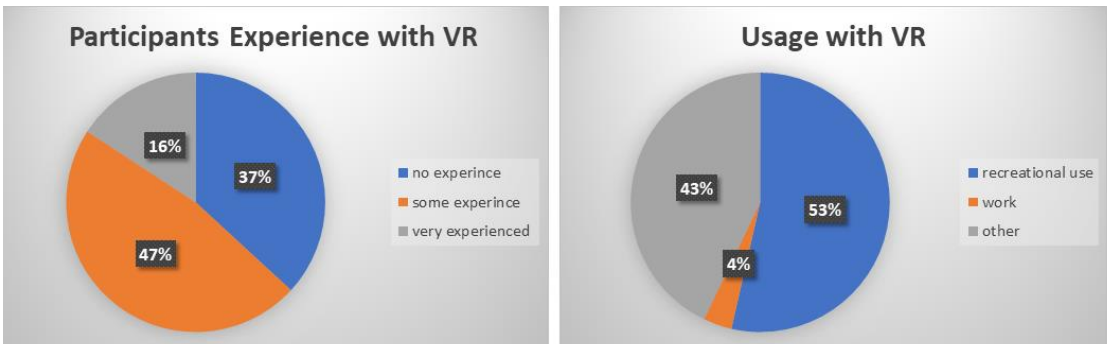


Figure 43: Participants experience with VR and what they have been using it for.

Embodiment Exit Survey Data Analysis

As discussed, earlier embodiment is defined as “the state of existing, occurring present in a place or thing. Embodiment has two factors that contribute it, one being presence the other being experience. With this definition in mind, there were several questions related to this in the exit surveys. The same questions were asked in both of the surveys. All the questions in the embodiment subgroup were multiple choice. A two-sample t-test was run to determine the relationship between the two VR simulations. Table 9 illustrates the p value between the CEV VR simulation and the Small Lunar Habitat VR simulation for each question. All but one question indicated towards the null hypothesis. The lighting tool pointed to the alternative hypothesis, the reasoning behind this could be the fact that each separate gaming engines have their own lighting and lighting display. A significant number of participants said the lighting tool in the lunar habitat was a lot more dynamic and immersive than the CEV simulation. Participants agreed both simulations were immersive and interactive. As discussed, earlier scale is a key component of embodiment, and in these two simulations only a handful of participants got the exact dimensions of the design correct in both simulations.

Table 9: Two-sample t-test data with the embodiment subgroup related questions for both surveys

Questions relating to embodiment	**CEV mean population**	**Small Lunar Habitat mean Population**	***p***	**Relation to threshold**
Did the virtual environment seem immersive?	0.935	0.870	0.401	>0.05
Did the virtual environment seem interactive?	0.967	0.870	0.167	>0.05
From your observation what do you think the length and height of the SHD is?	0.322	0.419	0.437	>0.05
Did the lighting tool give you a better perspective of the design?	0.774	0.967	0.025	<0.05
Did the mannequin/animated characters give you a better sense of scale within the SHD?	0.806	0.870	0.501	>0.05

Locomotion Exit Survey Data Analysis

Locomotion is defined as “an act or the power of moving place to place” [58]. The questions revolved around the mobility within the VR simulation and the objective reality. As discussed earlier if users can’t move efficiently within both then this can sour an experience and could serve ineffective for spacecraft habitat designers. Table 10 illustrates the p value between the CEV VR simulation and the Small Lunar Habitat VR simulation for each question. All the questions in the locomotion subgroup pointed to null hypothesis. Most participants in both simulations did not feel like the mobility was restricted in the virtual environment. In both simulations a significant number of participants had learning curve in getting comfortable moving in the virtual environment.

Table 10: Two-sample t-test data with the locomotion subgroup related questions for both surveys

Questions relating to Locomotion	**CEV mean population**	**Small Lunar Habitat mean population**	p	**Relation to threshold**
Did you feel your mobility feel restricted inside the virtual environment?	0.870	0.807	0.507	>0.05
Did it take some time for you to get comfortable moving in the virtual environment?	0.516	0.451	0.615	>0.05

Situational Awareness Exit Survey Data Analysis

Situational awareness is defined as "conscious knowledge of the immediate environment and the events that are occurring in it. Situation awareness involves perception of the elements in the environment "[59]. As discussed earlier when creating a VR simulation there are certain guidelines to follow when placing certain objects within the simulation. This will be important gauge VR technology's ability to help display certain aspects of design to the end user. In both exit surveys participants were asked if they noticed a certain object or image and this was different for each VR simulation. In the CEV VR simulation participants were asked if they noticed a picture of the Buzz Aldrin inside the CEV. In the Small Lunar Habitat VR simulation, participants were asked if they noticed a laptop inside the crew quarters. Table 10 illustrates the p value between the CEV VR simulation and the Small Lunar Habitat VR simulation for each question.

Table 11: Two-sample t-test data with the situational awareness subgroup related questions for both surveys.

Questions relating to Situational Awareness	CEV mean population	Small Lunar Habitat mean population	*p*	Relation to threshold
Did you notice "X" during the VR simulation?	0.419	0.838	0.01	<0.05

The data and analysis pointed towards the alternative hypothesis. More people were able to notice the laptop in the Small Lunar Habitat VR Simulation than the picture of Buzz Aldrin in the CEV VR simulation.

Usability Exit Survey Data Analysis

Usability is defined as "the quality or state of being usable, ease of use" [62]. The usability subgroup questions revolved around the participant's access to evaluation tools within the simulation and the evaluation objective tasks. Usability is incredibly important criteria when it comes to evaluating VR technology for SHD. As mentioned previously if participants can access all the evaluation tools and complete all the evaluation objectives without any difficulty, then it would show the usability aspect of VR technology could be trusted. On the other hand, if the opposite is true and participants are unable to access the evaluation tools and unable to finish the evaluation objectives. Then this could cause some concern on the usability of VR technology. In both exit surveys, participants were asked if they were able to access the evaluation tools, which evaluation tool was the hardest to use, and which evaluation objective was the hardest to accomplish. Table 12 illustrates the p value between the CEV VR simulation and the Small Lunar Habitat VR simulation for each question.

Table 12: Two-sample t-test data with the usability subgroup related questions for both surveys

Questions relating to Usability	**CEV mean population**	**Small Lunar Habitat mean population**	***p***	**Relation to threshold**
Were you able to access the evaluation tools?	1	0.96	0.217	>0.05
Which evaluation tool was the hardest tool to use?	0.774	0.354	0.01	<0.05
Which evaluation objective was the hardest to accomplish?	0.548	0.516	0.804	>0.05

All but one question indicated towards the null hypothesis. Participants were able to access the evaluation tools in both VR simulations. Although when it came to choosing which evaluation tool was the hardest, it was different in each simulation. In the CEV VR simulation the participants said the hardest evaluation tool to use was the measuring tape tool. In the Small Lunar Habitat, the answer was spread out, the material tool had the most saying it was the hardest evaluation tool, but all the other evaluation tools had their fair share.

Time Data Analysis

As mentioned earlier, each participant was timed during each VR simulation. They were timed from the moment they began the first evaluation objective until the last one was completed. Participants were not told beforehand that they would be timed. A time data analysis was employed to answer some key questions and assumptions. The first assumption do people with a technical background have less of a learning curve when using VR technology? Or could the opposite be true that even a person with no technical expertise or background finds using VR technology very intuitive. The other assumption is do people with prior experience with using VR technology have less of a learning curve in whatever VR simulation they are placed in. Whether it being recreational experience with it or professional work experience with it. As mentioned earlier 31 participants were collected, of the 31 participants five had a technical professional background. Three were very experienced with VR, 17 had some experience with VR, and 11 had no experience at all. Table 13 illustrates the time data average of each category with the participants. The longest recorded time for a participant to complete the evaluation objectives was 25 minutes which was in the CEV VR simulation. The shortest time recorded was 20 seconds which was in the Small Lunar Habitat VR simulation. Figure 44 shows a scatter chart of the time participants took in each VR simulation.

Table 13: Time data of different categories within the participants for both the CEV and Small Lunar Habitat VR simulations.

Participant category	**Number of Participants**	**Average time (minutes) CEV**	**Average time (minutes) Small Lunar Habitat**
All of the Participants	31	7.06	7.16
Technical professional background	5	4	4.24
Non-technical background	26	7.65	7.73
Some or very experience with VR	20	7.8	6.91
No experience with VR	11	5.7	7.6

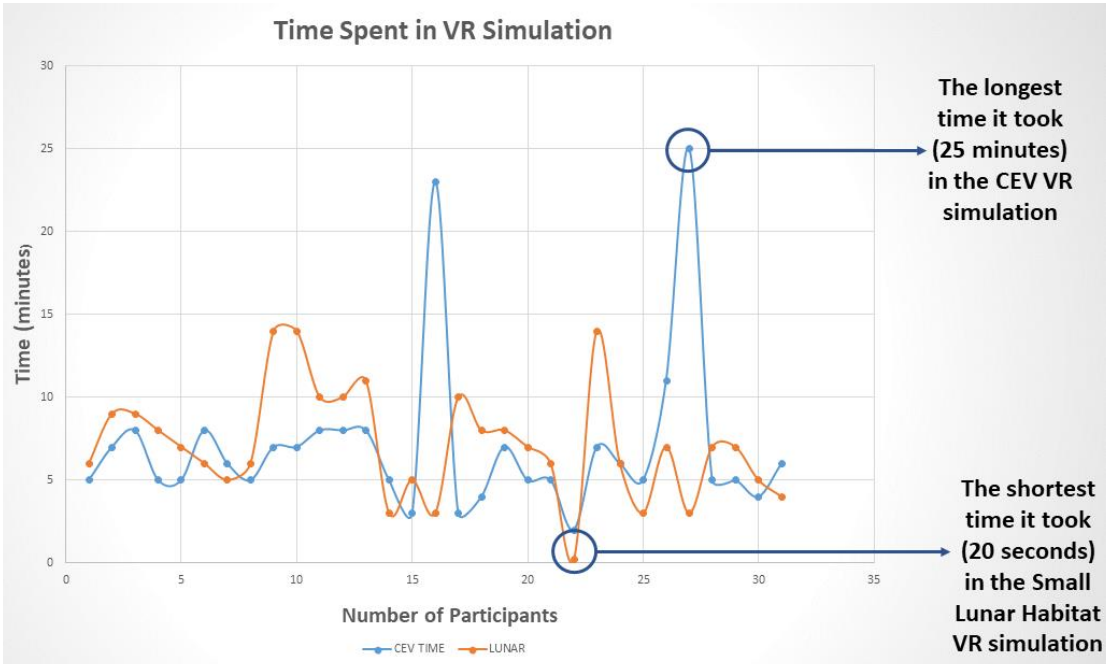


Figure 44: Scatter chart of the time each participant took in each VR simulation.

Discussion

After collecting the data necessary, interpretation of the data can now be done to evaluate the efficacy and efficiency of VR technology as a validation for SHD. Using the evaluation criteria set forth, efficacy and efficiency will now be determined for VR technology. For the embodiment category all but one question pointed towards the null hypothesis. VR was efficient in presence giving the participants an immersive and interactive environment in both simulations. Although one area VR technology failed to give a true sense of scale, as only a small group of participants were only able to accurately get the dimensions of the designs right in both simulations. This can be problematic for spacecraft habitat designers. Having a true sense of scale is important for design validation, and if VR cannot serve this purpose then it would lose its merit of incorporating it in the design process. Although there are methods to increase the sense of scale and making it more accurate. Increasing presence by making the simulation more immersive and interactive will help with sense of scale. Participants who accurately got the dimensions right of the design attributed it to the mannequin, animated characters, and measuring evaluation tool helped them in getting the dimensions correct. For spacecraft habitat designers who want to use VR to validate scale and volume of their designs. It is recommended to make the VR simulation as interactive and immersive as needed to truly get a sense of scale and presence. The lighting tool was different in each environment and produced different outcomes. Participants believed the lighting tool in the Small Lunar Habitat simulation was more immersive, dynamic, and gave them a better perspective of the design. As discussed earlier this stems from the fact that a different gaming engine was used from each simulation. Spacecraft habitat designers should keep in mind what kind of gaming engine is needed for their design and what of simulation they want to produce. Lighting in a simulation is something that cannot be overlooked. It can totally change the presence, scale, and immersiveness for the end user and could obstruct the outcome.

For the locomotion category, all questions were pointing towards the null hypothesis. Majority of the participants felt that their mobility was not restricted at all inside both VR simulations. However, the few participants who said they felt restricted was mostly from the CEV VR simulation. Participants who answered yes to feeling restricted inside the virtual environment were asked their reasoning behind it. Some said they felt like they wish they could have moved up and down to explore more of the vehicle and wish they could have “floated” inside the CEV just as you would in microgravity. This is an important finding, when wanting to validate a microgravity SHD in VR one should considered the aspect of moving as if they were in a microgravity environment. This could help validate and explore the design much more efficiently and effectively. Locomotion is something that needs to be explored more and will need to differ for a VR simulation that involves a microgravity SHD.

The situational awareness category had only one question, which pointed towards the alternative hypothesis. More participants were able to notice the laptop in the Small Lunar Habitat VR Simulation than the picture of Buzz Aldrin in the CEV VR simulation. There could be several reasons for this outcome. As mentioned earlier the Small Lunar Habitat was designed for a partial gravity environment, so the design is meant to be on the surface of the moon. The layout and interior of the design is similar in many ways as how we design for terrestrial architecture. People could have found this too be more analogous and easier to locate and navigate through their environment. Compared to the CEV design which was made for a microgravity environment, the layout and internal architecture is extremely different from what we experience in our day to days lives. Relating this back to the definition where it says situational awareness involves perception of the environment. Participants situational awareness in the Small Lunar Habitat being better than the CEV could be because of participants were able to relate more to the experience because it’s similar to what they normally experience in their day-to-day objective reality. This relates back to issue that was spoken in the locomotion category. Microgravity SHD VR simulations will need a different approach compared to its partial gravity SHD counterpart.

Lastly we have usability category, which only had one question which pointed towards the alternative hypothesis. Participants were able to access the evaluation tools in both VR simulations. There is merit in this given the fact that regardless of the user interface in each simulation participants were still able to access and interact with the evaluation tools. Although when it came to choosing which evaluation tool was the hardest, it was different in each simulation. In the CEV VR simulation the participants said the hardest evaluation tool to use was the measuring tape tool. In the Small Lunar Habitat, the answer was spread out, the material tool had the most saying it was the hardest evaluation tool, but all the other evaluation tools had their fair share.

This is was linked to the evaluation objectives, in both cases only one evaluation objective was hard to complete. The discrepancy of evaluation tools could stem from the fact that each VR simulation was created in different gaming engines. The CEV VR simulation was created in Unity, where one had to manually code all the evaluation objectives and tools. While in the Small Lunar habitat which used Twin motion as its gaming engine, the evaluation tool was already built in, no coding was involved. The upside is that all the participants were able to access the evaluation tools. There is concern with usability not being totally intuitive in both cases.

Looking at the time data, participants with a technical professional background had a lower average time than participants with no technical professional background at all. This raises concerns as to how well VR technology will be integrated in SHD. As mentioned previously SHD is a multidisciplinary field and not everyone working on a project has a technical background. This is a sample size test and of course correlation does not equal causation. It is still something to consider when working on a project where there will be individuals who don’t stem from a technical background having to work with VR technology. This could cause even more trouble and problems down the road in a project life cycle. Another comparable difference is the time it took for participants who had some or very experienced with VR compared to participants who had no experience at all. Participants with no experience recorded a shorter average time in the CEV VR simulation compared to participants who did have experience. For the Small Lunar Habitat participants who had experience recorded a slightly shorter time than participants with no experience. This shows promise as participants with no experience at all were able to complete the evaluation objectives just as fast as their experienced counter parts. Deducing from this VR technology might not have that big of learning curve as anticipated. This an extremely huge upside for spacecraft habitat designers who are looking to integrate this in the design process and not having to worry about the learning curve this technology brings to not only them but their cliental and stake holders.

CHAPTER 7: CONCLUSION

This research aimed to investigate whether VR can yield the creation of a successful experience that exceeded the time constraints a common SHD mockup walk through (low efficiency) or create a limiting experience where interaction and functionality were not executed to meet the required standards when it comes to evaluating SHDs (low efficacy).

Based on the quantitative and qualitative analysis of the two case studies, it can be concluded that VR for SHD has high efficiency and efficacy for partial gravity SHDs and low efficiency and efficacy for microgravity SHDs. Using two different SHDs and using two different gaming engines to create the VR simulation gave unique results and a greater breath of knowledge. The CEV case study showed that microgravity VR simulations must have different locomotion and situational awareness approaches. VR also did not have a steep learning curve as anticipated. Participants with no experience recorded a shorter average time in the CEV VR simulation compared to participants who did have experience. For the Small Lunar Habitat participants who had an experience recorded a slightly shorter time than participants with no experience.

Based on the conclusions made from the quantitative and qualitative analysis from the two case studies. VR technology could serve beneficial to SHD in early conceptual development in the project life cycle. While only some of the participants got the correct dimensions of the designs correct. The participants weren't the ones who built and modeled the designs. If a spacecraft habitat designer who built and modeled a design themself wished to get a true sense of scale of their design. Then VR could serve beneficial to them early in the design process. This gives spacecraft habitat designers another tool to investigate and validate their designs, and not solely relying on a 3D model on their computer screen. Thus, VR technology has great merit in early design phases during conceptualization. VR technology could serve beneficial later in the design process to replicate dynamic operations. Such as replicating concept of operation inside a SHD. This is an area that still needs to be verified to prove useful and beneficial to spacecraft habitat designers.

This thesis research raises more questions and discussions on well VR technology can be used and tailored to different SHD with different gravity designs. A different approach needs be taken with microgravity SHDs. Had the CEV and Small Lunar Habitat VR simulation replicated the exact surface gravity of the Moon and Ceres. This could have produced different outcomes in locomotion and situational awareness. As mentioned earlier replicating microgravity locomotion is tedious. Yes, it gives the user in the VR simulation a better sense of locomotion, immersive, and fidelity. Having a more immersive experience and fidelity isn't always conducive. As mentioned earlier, Bowman and McMahan note that sometimes high level of presence may not be necessary for applications and is an inefficient use of resources to go beyond what is required [6]. This is an area that still needs further investigation.

Future Work

There is still a need to further explore and determine the impact of VR towards the SHD process. While this thesis research has displayed VR's benefits in conceptualization early on in project design life cycle. There is a need to objectively look at specific, isolated design features to uncover the impact VR has towards the SHD field. Also, to uncover any other benefits VR might have in any other place in the project design life cycle. From the extensive research of this thesis referencing the other benefits VR has provided in other disciplines. Spacecraft habitat designers are urged to explore and expose the other potential benefits VR technology can bring. Not only that, but also to further investigate how VR can work within the project design life cycle.

Spacecraft habitat designers need to be continually thinking about the medium and what it can provide to enrich the SHD field. Deciding what makes sense to create and implement in VR and what doesn't. Therefore, requiring further experimentation and consideration. This thesis proposes that VR may be complex to integrate as part of the final visualization and verification stages to demonstrate higher fidelity. Its upside carries a much greater potential towards early design stages of conceptualization. Hopefully this thesis is able to differentiate between SHD VR design tactics and pinpoint areas of the project design lifecycle where spacecraft habitat designers can implement tactful experiential design as they develop a project.

Another consideration that requires further inquiry, is how spacecraft habitat designers can better convey designs with VR. As well as how VR can be advantageous over other design mediums. Further consideration could build upon the experimentation of this thesis and additionally evaluate other uses of VR and other XR mediums in the project design life cycle phases. Such an investigation might provide other definitive conclusions surrounding the VR design workflow. The research of this thesis was based on the understanding of a novice programmer, with a space architecture background. Exploring VRs utilization from different design professionals would also be worthwhile investigating.

With VR being consumer driven, expected technological advancements have the potential to increase usability of VR. Spacecraft habitat designers are encouraged to explore these technological upgrades and might discover other specific niches of VR in the project design life cycle. With potential advancements in future HMDs, this could mitigate some of the effort and limitation concerns experienced in this research. These potential upgrades could allow changes in range of motion and usability for VR users. Making the technology even more enticing to spacecraft habitat designers in discussion of locomotion and spatial experience.

Future HMDs with greater capabilities could also increase in complexity and add to further limitations as determined in this document. Re-conducting the experimentation in this thesis with future HMDs might provide worthy insight into the challenges VR still might face. This information could draw conclusions toward what developers might need to rectify for futures integration within the SHD field. Another area that warrants investigation is supplementing VR equipment with wearable biofeedback and neurofeedback equipment (i.e. EEG, EOG, EKG, and GSR) to better understand the neurological effects of SHD. As mentioned in chapter two, the research titled *Evaluating Educational Settings Through Biometric Data and Virtual Response Testing*. Where they used these devices in terrestrial architecture field, it might be worth investigating the same research within the SHD field. Experimentation conducted in the future with these technological advancements can therefor increase the clarity of VR technology’s role in the SHD field.

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