

# Pain Management for Spinal Cord Injury Survivors Using Virtual Reality

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**Abstract**—There are approximately 450,000 people suffering from Spinal Cord Injury (SCI) in the United States. There are about 10,000 SCI new cases in the United States per year. Individuals with SCI often suffer from neuropathic pain, which is difficult to diagnose, treat and manage. In recent years, technological advancements in the Virtual Reality (VR) field have made it feasible to investigate a possible role in using VR to treat neuropathic pain. VR-based distraction therapy is believed to have significant impact on increasing pain tolerance for SCI survivors. However, long-term pain management is still challenging. This study utilized different VR technologies, such as, mobile devices, Google Cardboard, and the Samsung Gear VR to facilitate a VR-based distraction experiment. Results suggest that all levels of immersive VR experiences have tangible benefits in pain management. If head-mounted display (HMD) devices are not available to individual survivors at home, smaller, portable mobile devices and tablets can also help reach the goal of pain management.

**Index Terms**—Anxiety, Depression, Fear, Google Cardboard, immersive, Mobile Devices, Neuropathic Pain, Rehabilitation, SCI, Samsung Gear VR, Unity, Unreal, VR

## I. INTRODUCTION

THERE are approximately 10,000 new SCI cases in the United States per year and about 450,000 survivors live with SCI [1]. SCI is a devastating and life-disruptive condition which significantly alters SCI survivors' life. In addition to all of the mental, physical, and lifestyle challenges that SCI survivors face, they also experience this phenomenon called neuropathic pain. Neuropathic pain affects 60 – 69% SCI survivors [2].

According to *Neuropathic Pain*, the International Association for the Study of Pain (IASP) has defined Neuropathic Pain as “pain initiated or caused by a primary lesion or dysfunction of the nervous system” [5]. Due to the medical complex nature, neuropathic pain is difficult to treat and manage. Currently, it is treated and managed by nonpharmacologic and pharmacologic means. It is also treated by Antidepressants and Anticonvulsants. However, treatment of neuropathic pain is still inadequate and unsatisfactory [3] [2] [4] [5] [6].

Treatment of SCI costs the United States more than 10 billion dollars each year [7]. Depending on SCI severity, patients are provided supportive care, medications, surgery, therapies,

medical procedures or drugs to reduce pain. However, no proven therapeutic treatments exist. Because of the complicated nature of SCI, there is not a personalized solution available to treat a wide range of SCI situations. This also causes the lack of improvement in SCI therapy [8].

Virtual Reality (VR) has been used to manage pain for over a decade. Research has also shown that VR helped reduce level of fear, anxiety, depression and pain [9] [10]. In recent years, immersive VR distraction applications have been used to manage pain with other clinical applications, such as, dental pain, burn wound pain, chemotherapy application, chronic pain, neuropathic pain, etc. [11].

However, past studies suggest that while VR-based control and distraction training may improve pain tolerance, pain threshold and reduce pain sensitivity in SCI survivors, it still provides only a relatively small reduction of pain intensity [9]. The developer in this study created a new VR game, Magic Forest Ride that expands upon the previous studies to examine new approaches towards pain tolerance and pain intensity improvement, as well as provide new means to manage the pain.

## II. BACKGROUND INFORMATION

Understanding of SCI background information helped the developer in this study determine the body constraints of the target audience and design an intuitive application for the target audience.

The spinal cord is critically vital to the functionality of the Central Nervous System (CNS). While the brain ceaselessly processes information, thoughts, and emotions, the spinal cord acts as the pathway between the brain and the nervous system throughout the body. By bridging signals across spinal nerves to and from the brain, the spinal cord is an essential catalyst for the coordination and influence of bodily activities. However, it is a complex structure, vulnerable to injury and disease that may lead to degradation of bodily function or chronic pain.

The spinal cord consists of thirty-one segmental levels and

extends from brain to cauda equine (or “horse’s tail”). There are eight cervical spinal nerves (C1- C8), twelve thoracic spinal nerves (T1 – T12), five lumbar spinal nerves (L1 – L5), five sacral spinal nerves (S1 – S5) and one coccygeal nerve [12].

Functions of nerves on each level vary. C1 through C4 cervical spinal nerves determine breathing, head and neck movement. C4 cervical spinal nerves through T1 thoracic spinal nerves determine heart rate control and upper limb movement (elbow through wrist C5 – C7 and Finger C8 – T1). T1 – T12 thoracic spinal nerves control trunk control, temperature regulation, and abdominal muscles. L1 – S1 lumbar spinal nerves control lower limb movement, such as, hip, leg and foot. S2 – S4/5 sacral spinal nerves define bowel, bladder and sexual function [12]. SCI is a damage in spinal cord or vertebral column or both which cause changes in its function. SCI is a complex situation in the medical field which still has a high death rate in low-income countries. It often happens unexpectedly which may significantly disrupt SCI survivors’ lives [12].

SCI can be classified as traumatic or non-traumatic. Traumatic SCI is the most common type of injuries which is caused by traffic accidents, falls, sports injuries or violence. Non-traumatic SCI, on the other hand, can result from infectious disease, tumor, and musculoskeletal disease. The most common areas of injury are at levels of cervical spinal nerves C5 through cervical spinal nerves C7 and thoracic spinal nerves T12 through lumbar spinal nerves L1. In other word, most SCI patients may have difficulty in controlling their upper limb movement, such as, elbows, wrists and fingers and lower limb movement, such as, hip, legs and feet [12].

According to *Recent Trends in Causes of Spinal Cord Injury* published by National Spinal Cord Injury Statistical Center, traffic accidents (vehicular accidents) ranked the first in causes of spinal cord injury, up to 39.08% of reported spinal cord injuries. Falls were ranked second at 29.54%. Violence was ranked third with 14.41%. Sports were ranked fourth with 8.39% of spinal cord injuries. All other causes accounted for 8.57% of spinal cord injuries [13].

Traumatic and non-traumatic SCI prevent the brain from receiving or sending information to the injured body parts. The level of changes on function of body parts depends on the severity of injury. Based on severity, SCI can also be classified as two types: Complete injury and incomplete injury. Patients suffering from complete injury lose motor function below the level of the SCI. Survivors with incomplete injury retain some sensory and muscular functions. Therefore, depending on the severity of SCI, survivors experience different symptoms and face different complications. Unexpected life changes totally disrupt their lives. They may experience mental health issues, such as, fear, anxiety and depression. Depending on their level of injury, they may also suffer from autonomic dysreflexia, deep vein thrombosis (DVT), hypotension, Urinary tract infections (UTIs), spasticity, sublesional osteoporosis,

heterotopic ossification, respiratory complications, and most importantly pain. Other than chronic pain and musculoskeletal pain, a significant number of SCI survivors suffering from neuropathic pain which leaves them feeling burning, stabbing, aching, and electric stinging sensations [12].

### III. LITERATURE REVIEW

Recent studies show that VR has been commonly utilized on pain management. It borrowed a traditional psychological intervention mechanism—distraction—to help patients ease their pain [9]. VR experiences can also influence the way patients think. Patients greatly benefited from the positive reinforcement that helped them reach a pain-free and relaxing state-of-mind [10].

Video games have been developed using VR as a platform, exploring the new possibilities for research and opening the door to clinical studies utilizing VR distraction towards pain management [14]. In addition to VR distraction, recent studies have also explored using VR as a mean for pain control [9]. HMD has been used to test VR applications in gaming, engineering and medicine to provide users an immersive experience. However, recent study also shows that traditional mobile devices can also provide an immersive experience sufficient to deliver pain management distraction [15].

#### A. Study I

*Differential Effects of Two Virtual Reality Interventions: Distraction Versus Pain Control* is a study on the difference between outcomes using VR distraction (VRD) and VR control (VRC) for pain management [9].

This study was conducted on two sets of variables, pain-related variables and cognitive variables. Pain-related variables were 1) intensity, 2) tolerance, 3) threshold, 4) time perception, and 5) pain sensitivity range. Cognitive variables were 1) self-efficacy and 2) catastrophizing [9]. There were 77 psychology students (70 females) from the University of Barcelona participated this study. Cold pressure apparatus and VR devices were used to aid the procedures. All apparatuses, VR devices and other variables considered by this experiment were the same [9].

Participants were randomly divided into three groups 1) control group (Non-VR), 2) VRD group and 3) VRC group. All participants were instructed to immerse their nondominant hands into cold water (6 degrees Celsius) with a maximum if immersion time of five minutes [9].

Control group participants had to look at a black screen during the immersion. VRD group participants were put in a VR mock surreal world environment where they could interact with surreal world objects and navigate through the VR environment in one hand. VRC group participants were engaged in a stereoscopic VR environment, which reinforced pain sensation; for example, burning, cutting, sharp, stabbing, and stinging, etc. This stereoscopic VR figure displays while unpleasant music playing in the background. Participants were

asked to improve their cold pressor pain sensation by adjusting the virtual figure and background music to a soothing one [9].

Comparing with the control group, VRC significantly increased three pain-related variables, pain tolerance, time perception and pain sensitivity range, and all cognitive variables. However, VRD significantly increased two pain-related variables, pain threshold and pain tolerance, with no effect on all cognitive variables [9].

### B. Study II

*The Effect of Coping Style on Virtual Reality Enhanced Videogame Distraction in Children Undergoing Cold Pressor Pain* is a study that aims to evaluate the effectiveness of using interactive video game with or without VR technology to distract patients from cold pressor pain [14].

There were 66 healthy children from age 6 to 15 who were selected from a university summer day camp to participate in this experiment [14]. The video game Sonic and the Secret Rings, developed by Sega for the Nintendo Wii, was used for this experiment. Within the Secret Rings game, the "Sand Oasis" level was selected because of its immersive design, engaging visual and audio incentive [14]. The 5DT HMD 3D virtual reality system was used to connect to Nintendo Wii system and television. Audio of the game was displayed through the HMD helmet [14]. A Neslab RTE 17 refrigerated bath circulator was used as the cold pressor. It maintained cold water with a temperature of 7 degrees Celsius [14].

This experiment utilized two trials to balance control and minimize potential errors caused by habituation to the cold pressor task [14]. The experiment was performed as follows: 1) traditional videogame with no VR technology involved; 2) VR assisted videogame; 3) trial two traditional videogame with no VR technology involved; and 4) trial two VR assisted videogame.

This study showed that interactive video game with or without VR technology, HMD VR helmet, is equally effective to distract patients from pain [14]. Also, based on a study of participants who experienced two trials, no evidence suggested that habituation could change the pain tolerance score [14].

### C. Study III

*Mobile Devices as Adjunctive Pain Management Tools* is a study focusing on the effectiveness of using VR software on mobile platform for neuropathic pain and pain management.

Three display methods were adopted by this study. They were mobile device, HMD, and standard flat-panel display (baseline). The results from mobile device display were compared with results from HMD and standard flat-panel display.

Twenty participants with low pain intensity score (<4) were selected to participate in control group experiment. Thirty-one chronic pain participants in 18 to 65 age group were selected to participate in the experimental group experiencing VR

distraction using HMD or mobile device. These patients had daily pain intensity score of greater and equal to 4 ( $\geq 4$ ).

The control group was asked to submerge their hands into cold water while they were experiencing VR distraction. Researchers measured the amount of time they were able to submerge their hands in cold water during: 1) flat-panel baseline display, 2) HMD, and 3) mobile device measurements. The experiment group was tested using HMD and mobile device [16]. Their results were compared with the control group. Various variables were measured, such as, heart rate, respiration, skin temperature, as well as, pain intensity.

This study provided strong evidence to support the effectiveness of pain reduction using VR distraction on mobile devices. Even though VR software on small portable mobile devices are able to reduce the pain significantly, it was not as significant as using a HMD with a fully immersive VR experience. Therefore, this study suggested HMD for clinical use and mobile devices for pain management at home [15].

## IV. PROJECT REQUIREMENT

The goal of this study was to design and develop a VR game to aid SCI survivors in managing neuropathic pain. As SCI survivors fall within a broad spectrum, the VR game targeted subject candidates that satisfy the following criteria. First, they must be currently suffering from SCI related pain or discomfort. Second, subjects should have sufficient vision and hearing to be able to respond to the stimuli of a VR application. Consequently, the VR application and hardware used in this research must be comfortable enough to wear on the head for an extended period of time without additional support from a third party.

The application should be accessible to individuals regardless of their ability to speak or walk; the VR headsets used should support an upright position either sitting or standing. The users must be able to utilize their fingers towards manipulating a trigger either on the VR device or in a hand-held controller.

To facilitate the creation of this application, a Git-based code repository and version control process has been put in place. Additionally, deployment of the application to devices used for testing or for experiments must follow an agreed-upon deployment procedure to ensure the latest code is deployed. Any software licenses, such as for Unity 3D or auxiliary software, that are necessary for development has been acquired and validated.

Before a subject was allowed to undergo an experiment utilizing the VR application, an eye test was conducted using an eye chart to ensure that the user had 20/20 eyesight to match the stereoscopic configuration of the Google Cardboard and Samsung VR headsets.

Similarly, subjects were tested for color deficient vision via an Ishihara plate exam. Additionally, subjects were tested for

hearing to ensure that they could reliably report on stimulus to spatial sound effects in the application, such as white noise.

## V. METHODOLOGY

This study aimed to design an immersive VR application with white noise audio effect to manage neuropathic pain. Experiments were conducted to measure changes in both pain-related variables and cognitive variables to determine the effectiveness of the VR distraction on reducing pain intensity and increasing pain tolerance.

### A. Variables

Pain-related variables studied were pain intensity, pain threshold, pain tolerance, and pain severity. Cognitive variables used by this study were self-efficacy and catastrophizing.

### B. Hardware

This VR game was built for Samsung Galaxy Series phones (S7+). It was predominantly tested on Samsung Galaxy S7 Edge model SM-G935F running with Android OS version 10.0.

This VR game was tested on Google Cardboard, which is compatible with both Android and iOS operating systems. This VR game was also tested on Samsung Gear VR headset, to give patients a HMD immersive experience. The Samsung Gear VR headset used in this study is compatible with Samsung Galaxy Series phones.



Fig. 1. Google Cardboard

### C. Software

This game was developed and tested using game engine Unity 3D version 5.5.2. Unity 3D is a commercial game engine that can be used to create real-time applications across a wide-range of devices, including but not limited to: Android OS mobile phones and tablets, iOS phones and tablets, PC computers and Mac OS computers and laptops. For this study, Unity 3D was licensed for personal use for educational purposes.

Unity 3D includes a license to SpeedTree technology which aids in the rendering and creation of vast floral resources such as trees and bushes. The 3D meshes used in the application were produced using Autodesk Maya 2017: a commercial toolset for creating 3D objects, characters, and vehicles for games, film, and animation. For this study, a student license of Maya was utilized which is valid for educational and research purposes. 2D images in this study were created using Gimp, which is a freeware image painting and manipulation tool. Additional resources were used from CGTextures.com, under a general-

purpose, free to use license. The compiled application includes the Unity 3D player for Android OS, and is deployed to the phone upon installation. The target device for this application must support at least Android OS version 9.0.

### D. Control Group

Ten (10) SCI survivors suffering from neuropathic pain were recruited to participate in this study as control group. These individuals had the same pain intensity score ( $\geq 4$ ) [17]. They had been suffering from SCI for approximately the same amount of time (3 years) and they exhibited similar symptoms. Subject candidates were tested for vision and hearing before being trained to use the application. The results gathered from control group was used as baseline data.

### E. Experimental Group

The same group, individuals participating as control group later participated as an experimental group. The results gathered from the experimental group was used to compare with its own baseline data to draw conclusions for this study.

### F. Procedure

Magic Carpet Ride application was first tested on a group of participants who did not suffer from SCI and neuropathic pain to determine the immersiveness of the VR application. This group of individuals were randomly selected from street or contacted directly by the developer. All testing results were recorded using Qualtrics survey via [https://pace.az1.qualtrics.com/jfe/form/SV\\_eWZUqyPMG3Cp.pqt](https://pace.az1.qualtrics.com/jfe/form/SV_eWZUqyPMG3Cp.pqt). Then, this application was tested by SCI survivors living with neuropathic pain to determine the effectiveness of pain management using VR reality.

Experiment participants in this study were measured on the set of pain related variables and cognitive variables mentioned in section A variables. The experiment was designed to last over a period of three days. During the first day, all participants were scheduled for similar activities in similar settings, without using any VR applications as distractions. After the course of the day, subjects were asked to self-report utilizing the questionnaire in Table 1. The next day, subjects would return to their previous schedule and settings, however with the addition of 20 minutes of gameplay with the developed VR application via a non-VR device, such as a mobile phone or tablet. Afterwards, subjects completed the same questionnaire. On the third day, subjects would again revisit their usual schedule and settings, however with the addition of 20 minutes of gameplay with the developed VR application through a Google Cardboard VR headset. Again, subjects would complete the questionnaire.

Finally, on the fourth day, subjects would be asked to resume their usual schedule and settings, with the final adjustment of experiencing the application through a highly-immersive VR HMD such as the Samsung Gear VR. Following the final experiment session, subjects completed the questionnaire in reaction to their immersive VR experience.

### G. Hypothesis

It is assumed that distraction via immersive VR applications, incorporating meditative elements such as white noise, poses

positive effects in regards to pain management and reduction. Furthermore, it is assumed that highly immersive HMD devices provide a larger net benefit towards pain management and reduction when compared to portable mobile devices or less immersive VR equipment such as Google Cardboard.

#### H. Measurement

Neuropathic pain is currently diagnosed and measured by clinics using clinical examination, pain questionnaires and diagnostic tests [17]. For the purpose of this experiment, pain questionnaires were the first choice due to their traditional reliable as screening devices. Measurement on pain-related variables and cognitive variables were evaluated and recorded on a daily basis over the course of the experiment, per subject. Experiment facilitators kept thorough records of each patient’s activities and self-reported feedback.

Subjects were asked to rate the influence of each factor on their overall experience on a scale from 1 to 5; 1 meaning little to no influence, and 5 representing very strong influence.

Pain intensity refers to the strongest level of pain experienced throughout the current phase of the experiment. For instance, on the first day, it would be the maximum level of pain experienced in traditional schedule and setting. For the second, third and fourth days, it would be the maximum level of pain experienced over the course of the gameplay session.

Pain tolerance refers to a subject’s ability to withstand pain, such that it does not become burdensome. In this case, the scale ranges from 1 to 5: 1 meaning that the subject’s pain is unbearable, preventing the subject from focusing on other tasks, while 5 may represent that the subject is able to focus on other tasks freely in spite of any pain experienced.

Self-Efficacy in the case of this study is meant to include three scales. First, a subject’s own reported ability to tolerate pain. Second, a subject’s own reported ability to manage and reduce pain intensity. Third, a subject’s own assessment in their ability to report on their experiences of pain.

Last, subjects complete the Pain Catastrophizing Scale [15], which allows subjects to apply a 5-point scale towards their past experiences of pain. This grants a window into the subject’s morale regarding their SCI-induced pain; it allows a subject to self-report on their emotional state and helplessness due to their pain. Self-reported perceived debilitation implies a stronger benefit via VR application distractions for individuals who reported decreasing pain intensities and/or increased pain tolerance over the progression of the experiment. This scale can be accessed via SurveyMonkey.

(<https://www.surveymonkey.com/r/YQML392>)

#### I. Evaluation (Questionnaire)

In addition to the questionnaire in Table 1, subjects were asked to rate their experience using the application itself. Each category was to be rated on a scale from 1 to 5, with 5 indicating the highest satisfaction. The data collected from this report was utilized to serve multiple purposes. First, it can be determined what correlation, if any, exists between the user experience of a

VR application and its clinical benefits. Second, the feedback is valuable towards the future improvements and maintenance of the application, in case it has any clinical or experimental value in the future. This evaluation questionnaire can be accessed via Qualtrics Survey. Magic Forest Ride was first tested by a group of people who did not experience from SCI. Experiment results were gathered and compared to further study the how immersive this experience was. This application was then tested by a group of SCI survivors who suffered from SCI and experienced with neuropathic pain.

	1	2	3	4	5
Ease of using the application					
Interest in the application					
Immersiveness of the application					
Comfort of the VR headset					
Level of pain or discomfort when VR session begins					
How likely they were to recommend the application to other SCI survivors					

Fig. 2. VR Application and Headset Satisfaction Survey

## VI. APPLICATION DESIGN AND TESTING

### A. Application

Magic Forest Ride is an original game that was designed and built from scratch for the purposes of this study: Pain Management for SCI survivors Using Virtual Reality. The primary goal of this game is to utilize audio-visual VR-based distraction to provide a relaxing and enjoyable experience for SCI survivors suffering from neuropathic pain.



Fig. 3. Magic Forest Ride Game Scene I

In this game, subjects experience a magic carpet ride through a forest-like environment. The ride is experienced through a first-person perspective: the user’s point of view is anchored to the carpet itself. By utilizing a VR headset, the user is able to tilt and pivot the view simply by moving his or her own head.



Fig. 4. Magic Forest Ride Game Scene 2

During the gently-paced ride, the magic carpet will follow a softly-meandering path through a virtual forest. To provide the most enjoyable experience and counter-act effects of simulation sickness, the following constraints are imposed on movement:

- The magic carpet can only move horizontally; there is no vertical movement.
- The magic carpet will always remain level.
- The camera must match the user's own head motion 1:1 without noticeable delay.
- The magic carpet follows a predefined path; the user is unable to direct the carpet's movement or subsequently become lost.
- The magic carpet moves slowly to allow the user to comfortably acclimate to the virtual environment

Additionally, the game's design directly addresses the constraints of stereoscopic VR solutions (such as the Google Cardboard and Samsung Gear VR):

- A cartoony aesthetic has been chosen, with mostly solid colors, in order to make object boundaries more readily apparent.
- A reticle is always present at the center of the user's field of vision. When an interactive object is gazed at by the user, the reticle expands.
- The game was optimized to run at 60fps on targeted hardware (Samsung Galaxy S7 Edge)

Aside from gaze, the user is able to trigger magic powers to collect fruit from trees. This trigger is activated via the magnetic or physical triggers available on Google Cardboard and Samsung Gear VR headsets. Throughout the player's flight, there are trees bearing glowing fruit that the player is able to collect. By gazing at a tree and engaging the VR trigger, the tree's fruit are levitated away and added to the player's score. At the end of the flight, the subject is informed of how much fruit he or she was able to collect.

This scoring mechanism serves only to engage the subject's attention. The game is paced slowly enough that there is no urgent sense of competition, and player scores are kept confidential from each other; there is no "high scores" table logged. While the gameplay rules were clearly explained to each subject, they were also each free to explore the game as they desire. If they felt immersed enough simply by gazing

upon the environment, then the distraction was considered to be in effect and they were not actively encouraged to pursue fruit by the experiment facilitators.

A single carpet ride lasts between two and three minutes, and subjects were allowed to replay the game as many times as they liked within a 20-minute limit.

Through this game, individuals experienced a magic carpet ride through a forest. By using magic powers, via a trigger button, they were able to collect fruits along the way before the ride was complete.

The experience of flight on a magic carpet contradicts the physical constraints experienced by SCI survivors in the real world. Research shows that this contradiction of experience aids the patient with coping with neuropathic pain [11].

Furthermore, by utilizing a magic carpet, it provides the same potential level of immersion to all SCI survivors, regardless of their mobility. For instance, if the path were walked by a virtual avatar, the results may be confounded cognitive dissonance if the subject is unable to walk.

The environment was chosen due to its ample opportunity for calming effects that occur in nature, including the following:

- Sounds of running water and peaceful wildlife
- Audiovisual cues of wind such as swaying grass
- Warm, orange color scheme of autumn
- Sensation of being far from city traffic and commotion

Additionally, the magic fruit encountered by the subjects occur in bright pastel colors.

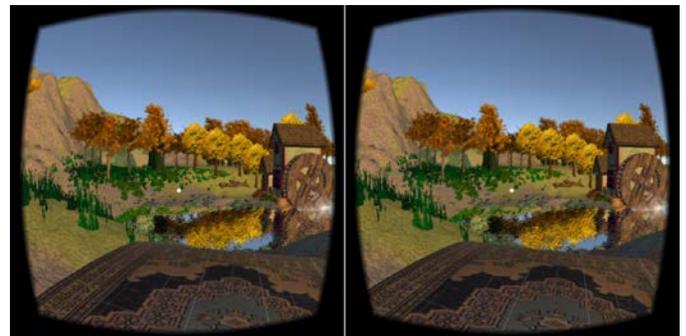


Figure 5: Magic Forest Ride Game Scene 3, as viewed through Google VR simulator within the Unity 3D editor 2D vs 3D

This application was developed on the assumption that a VR device is not inherently immersive; applications must be designed to immerse the user.

It is possible to port mouse-and-screen user interfaces for use in a VR headset, but this approach was not assumed to provide the same psychologic or audiovisual experience as a point of view into a full 3D world.

Thus, one of the main reasons this application was chosen is because it provides a first-person point of view into a fully-

detailed virtual world. This application was designed from the ground-up to take advantage of VR hardware and user interfaces.

### B. Architecture Design

Magic Carpet Ride was developed within Unity 3D, a commercially available game engine. Thus, the application architecture inherently differs from traditional applications in the following ways: Unity applications are based on game objects that can possess any number of behavioral components; Unity utilizes a common development path through C# or JavaScript that is then compiled to the target system's format; Unity provides the core functionality of a 3D application, such as displaying 3D objects and playing sound.

Magic Carpet Ride was developed using C# as a scripting backend. The following diagram illustrates the high-level relationship of how custom assets were combined with the Google SDK running on Unity to be deployed to the Samsung Galaxy S7 Edge.

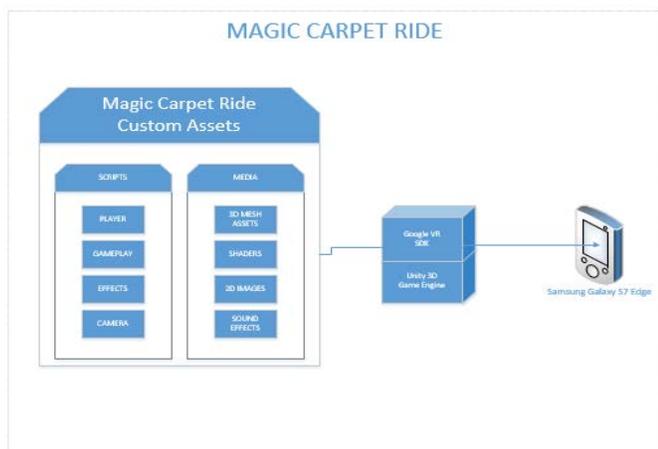


Figure 6: High-level design of how custom assets for Magic Carpet Ride are implemented in a Unity 3D application that can be deployed to the Samsung Galaxy S7 Edge smartphone.

While much of Unity 3D's inner-functionality acts as a "black box", the components in a Unity 3D application still hold dependencies and interactions on each other that can be clearly documented. Below is a lower-level detail of the interactions of the major components of Magic Carpet Ride. Android OS triggers a regularly occurring update cycle in Unity 3D, in which we use to advance scenic effects and the magic carpet's movement directly without additional player input. Isolated from the update cycle, the player component responds to user input by moving the camera in conjunction with the user's head and responding to trigger events. A global Game State singleton acts to hold the current tally of collected fruits, which is updated whenever a group of collectable fruits is activated via player click. At the end of the ride, the game state will then be retrieved to alert the user of how much fruit was collected during the flight.

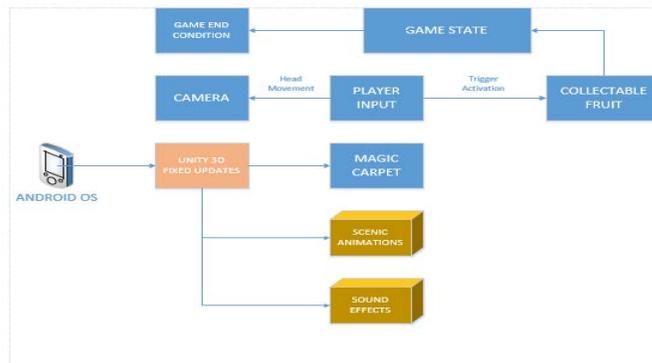


Figure 7: Low-level design of Magic Carpet Ride major components. The majority of logic is split between regularly occurring updates in the scenery and responding to player input.

## VII. RESULTS

Magic Forest Ride game was built and tested by a developer and group of individuals who did not experience SCI and neuropathic pain. The primary goal of this experiment was to determine immersive user experience. Within one day, this experiment gathered 58 responses from 28 males and 33 females, on Immersive Tendencies Questionnaire (ITQ) and Presence Questionnaire (PQ) through Qualtrics. 95% of population found the application was easy to use and learn. 93% of the population found the application environment was completely responsive to actions they initiated. 97% individuals indicated that there were absolutely no delays between actions and outcomes. And 90% of the population indicated that they were completely engrossed in the VR experience. Additionally, this application achieved frame rates of 90-180fps and on the development PC. On hardware, the application produced a frame rate of 60fps, which feels smooth enough given the slow movement of the magic carpet. Additional experiments will be conducted by Burke Medical Research Institute on SCI survivors to determine the effectiveness of using this application to manage neuropathic pain.

## VIII. CONCLUSION

Magic Carpet Ride was created to observe the potential for VR distraction towards alleviating neuropathic pain experienced by SCI survivors. In order to produce an immersive experience, it was vital to reduce any choppiness in rendering the virtual scene. Choppiness immediately broke the immersion when using a VR headset such as the Google Cardboard. However, when viewing the game on a computer screen or non-VR device, the impact of lower frame rates was lessened.

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