PROJECT SUMMARY

Overview:

The effects of cybersickness (i.e., motion sickness caused by immersive simulation, such as virtual reality) on healthy users has been one of the fundamental research areas in virtual reality(VR) for many years, but its impact on persons with physical disabilities is still unknown, even though it could have a significant an impact on VR-based physical rehabilitation. The PI proposes to investigate cybersickness for persons with disabilities, specifically for persons with multiple sclerosis based on specific selection criteria (e.g., a moderate level of mobility impairment but without cognitive disability). The expected outcome of this research is to minimize negative effects of cybersickness for disabled persons, thereby significantly improving VR physical rehabilitation effectiveness and ultimately quality of life.

Intellectual Merit :

The objective of this proposal is to determine the best ways of measuring cybersickness in disabled persons and understand the main factors that contribute to cybersickness disabled persons, specifically for users with proprioceptive and balance deficits (e.g., due to neurological, vestibular, balance issues). Based on preliminary data, the central hypothesis is VR induced cybersickness will be magnified for persons with disabilities as compared to healthy persons based on differences in balance and proprioception abilities, which may also require new approaches to measuring cybersickness in disabled populations. To test this hypothesis, the PI proposes aims that together effectively measure and ultimately aim to minimize VR induced cybersickness in disabled persons. Specifically, the PI aims to 1) determine how disabilities correlate with VR induced cybersickness, 2) determine the most effective objective metrics of VR induced cybersickness for disabled persons, 3) determine the main contributing VE design aspects that affect cybersickness for disabled persons and 4) create, disseminate, and maintain an open database of deidentified cybersickness data of disabled persons. Through a series of empirical studies, the PI expects to provide an understanding of how cybersickness in VR affects persons with disabilities, such as mobility impairment due to multiple sclerosis. The proposed work is significant because it has potentially negative implications for the effectiveness of VR rehabilitation and more generally it is a critical step towards the grand challenge of universal usability in VR. This work will offer a deeper understanding of the effectiveness of VR as a medium for rehabilitation.

The proposed work is creative and original because: although there is much research on the effects of cybersickness in healthy persons, there is minimal research on how cybersickness affects people with disabilities. Thus, this research is potentially transformative because it may disrupt accepted theories and perspectives of the effects of cybersickness in VR and revolutionize design guidelines for VR rehabilitation.

Broader Impacts :

The proposed research has broader impacts in three major areas: broad societal impact, community outreach for persons with disabilities, and involvement of underrepresented minority students in research. The proposed work has a broad societal impact because the ultimate goal is to increase the effectiveness of VR physical rehabilitation. The PI expects that the effects of cybersickness will significantly impact the way that users perform exercises, could potentially have long term impact on the effectiveness of the rehabilitation, and ultimately quality of life. Furthermore, if the central hypothesis of this proposal is found to be supported, this work may inspire other researchers in VR to develop approaches to combat cybersickness specifically for disabled persons, which will also produce further vertical advancement in the field.

The PI plans to integrate results research and education in a novel course: Accessible User Interfaces and Universal Usability. Through this class the PI will actively engage graduate and undergraduate students in research, and will use the results of the proposed work to help recruit more students into research and spawn new independent research projects. Moreover, more than 59% of UTSA's students come from groups underrepresented in higher education.

Project Description

CAREER: Measuring and Reducing Cybersickness in Virtual Reality Physical Rehabilitation

1. Overview and Objectives

Understanding the effects of cybersickness has been one of the fundamental research areas in Virtual Reality (VR) research for many years, but the effects of cybersickness on persons with physical disabilities is unknown, even though it could have a significant an impact on VR-based physical rehabilitation. Cybersickness in VR is a similar phenomenon to motion sickness, except that it is caused by exposure to a simulated environment (e.g., a virtual environment (VE)). Users who experience cybersickness may have feelings of nausea or dizziness, for example. The effects of cybersickness on VR users has been studied extensively since the 90s but is still considered to be one of the primary factors that affects interaction performance and subjective impressions of VR. However, everything known about cybersickness and how to measure it was gathered from research with healthy, normal subjects. It is unknown how cybersickness impacts users with physical disabilities, especially users with proprioceptive and balance deficits, which are common for users with neurological problems (e.g., multiple sclerosis, stroke, spinal injury). Disabled populations are the majority of the users of VR rehabilitation. Thus, it is important to understand how cybersickness affects persons with disabilities, since it could have a significant impact on the effectiveness of VR rehabilitation and ultimately quality of life.

The *objective* of this proposal is to determine the best ways of measuring cybersickness in disabled persons and to understand the main factors that contribute to cybersickness disabled persons, specifically for users with Multiple Sclerosis (MS), who commonly have proprioceptive and balance deficits (see *Section 5.5.2 Populations, Selection Criteria, and Screening Process*). The long term goal is to investigate how cybersickness impacts VR rehabilitation. *Our central hypothesis* is: VR induced cybersickness will be magnified for persons with disabilities as compared to healthy persons based on differences in balance and proprioception abilities, which may also require new approaches to measuring cybersickness in disabled populations. This hypothesis is based upon preliminary results of a study conducted with disabled persons – specifically mobility impaired (MI) persons - and healthy persons in VR. The MI participants had deviated gait (i.e., walking patterns), balance issues, and walked with canes. We used the common simulator sickness questionnaire (SSQ)[Kennedy, Lane et al. 1993] to measure cybersickness. When MI persons walked through a realistic virtual environment (VE), they experienced an increase in cybersickness symptoms, whereas healthy participants did not experience a significant difference. Moreover, for the MI participants only, we found a significant correlation between SSQ scores and the subjective ratings of VE realism – that is, when MI participants experienced more cybersickness, they also judged the VE to be less realistic. We expect that even a small amount of cybersickness may have a major impact on disabled user s' performance and subjective feedback. The literature supports this idea at least for healthy users. Kennedy et al. in 1995 [Kennedy, Lane et al. 1993], Kolasinski et al. in 1998 [Kolasinski and Gilson 1998], and Suma et al. in 2009 [Suma, Finkelstein et al. 2009] and others [DiZio and Lackner 2000, Liu and Uang 2011] all come to the same basic conclusion that cybersickness is one of the primary factors that influences performance and subjective impressions of VEs. Throughout this time, there has been a significant amount of research for enhancing rehabilitation with VR (e.g., [Rand, Kizony et al. 2004, Eng, Siekierka et al. 2007, Tierney, Crouch et al. 2007, Flores, Tobon et al. 2008, Flynn, Lange et al. 2008]), but the effects of cybersickness have been minimally studied with regard to populations who typically participate in VR rehabilitation – persons with disabilities. Upon the success of the proposed research, we expect to provide new insight into the effective measurement, symptoms, and causes of cybersickness for MI persons, which can then be used to reduce cybersickness in VR rehabilitation, and ultimately increase the universal usability of VR in general.

Aim #1 Determine how disabilities correlate with VR induced cybersickness: The *working hypothesis* is: cybersickness will be increased for disabled users and certain SSQ factors will be correlated to certain disability characteristics, such as self reported level of balance problems and vertigo, which are mostly unique to disabled users. By obtaining a better understanding of how the SSQ impacts and assesses disabled persons' cybersickness, VR rehabilitation practitioners and researchers can more effectively predict and assess the impact of cybersickness on their disabled patients.

Aim #2 Determine the most effective objective metrics of VR induced cybersickness for disabled persons: The *working hypothesis* is that objective measures such as gait analysis, Electroencephalography (EEG) [Chen, Duann et al. 2010], and optokinetic afternystagmus (OKAN)[Guo, Ji et al. 2011] will be effective surrogate (i.e., highly correlated) measures of cybersickness for disabled persons. Currently the SSQ is the most common cybersickness measure for healthy persons. Although the SSQ is simple to administer, it can increase cybersickness effects after multiple SSQs, which may potentially be increased with disabled users. This makes it logistically difficult to use in within-subjects studies, which are the study design of choice when working with disabled participants (i.e., due to the high occurrence of individual differences). Determining objective cybersickness measures for disabled persons will make prediction and assessment of cybersickness in VR rehabilitation more effective.

Aim #3: Determine the main contributing VE Design factors that affect cybersickness for disabled persons: The *working hypothesis* is that the main controllable VE aspects (e.g., Field of View (FoV), peripheral occlusion, depth cues) that contribute to cybersickness for healthy persons will be the same for disabled persons, but the specific VE design aspects related to balance and "head sway" will magnify cybersickness in disabled persons. By identifying the primary VE design aspects that impact cybersickness, we can inform the design of effective VR rehabilitation environments and potentially enable the design of VEs that minimize cybersickness effects.

Aim #4 Create, disseminate, and maintain an open database of deidentified cybersickness data of disabled persons: To enable a vertical advancement in cybersickness research in VR rehabilitation, there is a significant need for a community accessible database of cybersickness data that focuses on disabled persons. Currently, there are datasets of cybersickness SSQ data for healthy individuals [Kennedy, Lane et al. 1993, Brooks, Goodenough et al. 2010], but none that include disabled individuals. Our *approach* is to create and maintain a web-based portal for accessing and adding to this database.

Qualifications of the PI: Intellectual and Physical Resources: The PI is uniquely qualified to lead this research. Firstly, the PI and his research team at UTSA have conducted novel preliminary work to understand the effects of VR on persons with disabilities, which creates a necessary foundation for the hypotheses that drive this proposal. Secondly, the PI has developed collaboration with the Neurology Institute of San Antonio (NISA) and its in-house physical therapy office: the Rehabilitation and Wellness center. Led by a renowned expert in MS, Dr. XXX (see *letter of collaboration*), NISA provides clinical care and rehabilitation to more than 900 M.S. patients – the target population for the proposed research

The proposed work is *creative and original* because: although there is much research on the effects of cybersickness, there is minimal research on how cybersickness affects people with disabilities. Thus, this research is potentially ***transformative*** because it may disrupt accepted theories and perspectives of the effects of cybersickness in VR and revolutionize design guidelines for VR rehabilitation. Specifically, we expect that we will be able to 1) effectively measure and predict cybersickness in disabled persons and understand its symptoms (aims 1 and 2); 2) identify the primary VE design aspects that affect cybersickness for disabled users so that VR rehabilitation can be more individually tailored to the needs of persons with disabilities (aim 3); 3) similar to the databases of healthy persons' cybersickness data[Kennedy, Lane et al. 1993, Brooks, Goodenough et al. 2010], the proposed database of disabled persons' cybersickness data will enable vertical advancements in the field. Specifically, the results of our studies and the database will enable us to effectively assess and predict cybersickness in disabled persons, and will help VE rehabilitation programs and VR system designers to focus on the unique needs of persons with disabilities. This research will ultimately lead to reducing the effects of cybersickness for disabled persons in VR and significantly improve the effectiveness of VR rehabilitation.

2. EXPECTED SIGNIFICANCE

The effect of cybersickness on persons with physical disabilities is unknown, even though it could have a significant an impact on disabled users in VR-based rehabilitation. *The proposed work is significant because it has potentially negative implications for the effectiveness of VR rehabilitation and more generally it is a critical step towards the grand challenge of universal usability in VR.* That is, this work will 1) offer a deeper understanding of the effectiveness of VR as a medium for rehabilitation 2) potentially inspire new thinking about how to combat cybersickness specifically for persons with disabilities and 3) ultimately improve quality of life for persons with disabilities.

3. RELATION TO THE PRINCIPLE INVESTIGATORS LONG TERM GOALS

From a basic science perspective, the PI wants to understand how to design effective virtual experiences for persons with disabilities, how fundamental VR factors (e.g., presence, latency, navigation, 3D interaction, cybersickness etc.) affect this experience for persons with disabilities, and how virtual environments can be designed to accommodate and assist persons with disabilities. The PI has already begun exploring presence, navigation, and latency (see *preliminary studies and prior NSF support*). In the future the PI will continue to investigate other fundamental aspects of VR and their impact on users with disabilities.

4. BACKGROUND

4.1. Review of Relevant Literature

This section reviews the primary areas where we found a gap in knowledge: between Cybersickness and VR rehabilitation.

4.1.1. Cybersickness in VR

Symptoms of Cybersickness: Cybersickness[Stanney, Kennedy et al. 1997] symptoms are similar to motion sickness symptoms, but are only experienced in systems with digitally presented feedback, such as in VR systems. The most common symptoms include pallor, sweating, and salivation. Major reported symptoms also include nausea, drowsiness, general discomfort, apathy, headache, stomach awareness, disorientation, fatigue, and incapacitation. Sometimes postural changes will occur, which can also be a symptom of cybersickness.

Theoretical Causes of Cybersickness: Over the years there has been considerable debate on the causes of cybersickness. Currently, there are primarily two theories [Kolasinski 1995, Kolasinski and Gilson 1998] that are each widely accepted, depending on literature citing them: 1) cue conflict theory and 2) postural instability.

Cue conflict theory is the phenomenon that occurs when two sensory channels detect cues that conflict with each other. For example, in a virtual environment it is common for the visuals to indicate the user is moving forward, but the user is standing in one spot in the real world. This conflict between the visual and vestibular senses may cause to cybersickness.

Postural instability (i.e., ataxia) occurs in VEs when the user has yet to adapt his/her movement to the system and learn strategies to maintain postural stability. For example, when users first use a virtual environment system, they often walk slower, presumably to compensate for postural instability. This phenomenon is thought to cause cybersickness.

Measuring/Predicting Cybersickness: For many years, effective measurement and prediction of cybersickness has been a major area of research, but has focused mainly on healthy people.

The most widely used apparatus for measuring cybersickness is the Simulator Sickness Questionnaire (SSQ) [Kennedy, Lane et al. 1993]. This questionnaire was originally derived from the standard motion sickness questionnaire[Kellogg, Kennedy et al. 1964], but was refined for use specifically with simulator induced motion sickness. In VR, simulator sickness is known as cybersickness [Stanney, Kennedy et al. 1997] due to the slightly different foci of symptoms. The SSQ consists of 16 symptoms rated on a 4 point Likert scale. The 16 symptoms are divided into three scales Nausea, Oculomotor, and Disorientation. The scores for each scale are added and weighted to obtain a total score of cybersickness.

For many years, the SSQ was used in repeated measures studies as pre and post tests, but more recently it has been shown that multiple administrations of the SSQ can actually increase cybersickness [Young, Adelstein et al. 2007]. Instead, it is now recommended to administer only 1 SSQ per session and compare it to baseline data healthy user's baseline SSQ scores from the original database [Kennedy, Lane et al. 1993].

Due to the confounds that multiple SSQ administrations may introduce, more objective, indirect measures have been proposed. Posture changes and head rotation[Liu 2009] have been used to measure cybersickness, although with varying degrees of precision[Hamilton, Kantor et al. 1989]. More recently, methods that use Electrooculograms (EOG) – a measure of eye movement – have been used [Guo, Ji et al. 2011]. Specifically, the authors investigated cybersickness as it correlates to a particular type of eye movement - optokinetic afternystagmus (OKAN) - a type of eye 'jitter' caused by the vestibular system (i.e., balance determined by the inner ear). OKAN is an effective metric to predict susceptibility to cybersickness. Other objective measures include EEG[Chen, Duann et al. 2010], Heart rate variability[Zużewicz, Saulewicz et al. 2011], and galvanic skin response (GSR) [Kennedy, Drexler et al. 2010].

Factors that Influence Cybersickness: There are three classes of factors that are known to influence cybersickness 1) individual, 2) simulator, and 3) task (table 1).

Table 1. Factors thought to be associated with cybersickness in healthy users[Kolasinski 1995]. Proposed factors to be investigated for disabled persons in the proposed work are in bold italics.

Individual Factors	Simulator Factors	Task Factors
Age	Binocular viewing	Degree of control
Concentration level	Calibration	Duration
Ethnicity	Contrast	Head movements
Experience with the real world task	***Field of view***	Method of movement
Experience with the simulator	Resolution	Rate of rotational acceleration
Gender	***Scene Content***	Rate linear acceleration
Illness and personal characteristics	System latency	Self movement speed
Mental rotation ability	Position tracking error	Sitting vs. standing
Postural stability	Inter-pupillary distance	Vection

However, almost all of the research behind the identification of these factors has been conducted with healthy people. Instead, the proposed research focuses on persons with disabilities. Based on our preliminary studies, we propose to investigate the specific factors of illness and personal characteristics (aims 1 and 2), field of view and scene content (aim 3). The remaining factors are also likely relevant to cybersickness in disabled persons, and thus are included in the PI's long term interests.

NOTE: In all of the previously mentioned work studying cybersickness, participants were generally able bodied, healthy individuals. We aim to study disabled persons.

Cybersickness in the Elderly: Besides our own preliminary work, the main work that effectively motivates the proposed research is the few studies of elderly users' experience of cybersickness [Liu 2009, Classen, Bewernitz et al. 2011, Liu and Uang 2011, Parijat and Lockhart 2011, Kawano, Iwamoto et al. 2012]. In general, it is known that increased age is correlated with increased cybersickness. There are many theoretical reasons for this. For example, with increased age also increases postural instability, which can impact cybersickness. Likewise, one would expect a similar effect from persons with disabilities. However, persons with disabilities have fundamentally different causes and levels of severity for their postural instability and thus may experience different effects and need different measures.

4.1.2. VR Rehabilitation and Games:

VR has significant benefits to rehabilitation. A VE is not subject to the dangers and limitations of the real world [Boian, Sharma et al. 2002, Burdea 2003, Wood, Murillo et al. 2003, Merians, Poizner et al. 2006], which expands the types of exercises that patients can practice, while still having fun in the case of VR games. In general, research suggests that VR and VR games have measurable benefits for rehabilitation effectiveness [Sveistrup 2004, Eng, Siekierka et al. 2007, Ma, McNeill et al. 2007, Crosbie, Lennon et al. 2008, Adamovich, Fluet et al. 2009] and motivation [Betker, Desai et al. 2007, Verdonck and Ryan 2008].

Visual Feedback: Visual feedback is any kind of feedback for rehabilitation delivered to the patient through the visual modality. This includes mirrors, computer displays, and VR. Visual feedback has been shown to be effective in rehabilitation [Sütbeyaz, Yavuzer et al. 2007, Čakrt, Chovanec et al. 2010, Thikey, van Wjick et al. 2011]. However, the impact of cybersickness induced by visual feedback (VR or otherwise) has not been studied with disabled persons.

Gait Rehabilitation: Gait (i.e. walking) rehabilitation is the main type of rehabilitation that requires navigation in a VE. These systems used a head mounted display (HMD) or a large LCD screen. HMDs are more immersive than screens. The user's view is completely replaced and the head is tracked to afford the user natural head movement. Results were positive [Fung, Richards et al. 2006, Tierney, Crouch et al. 2007, Bardack, Bhandari et al. 2010].

Design Guidelines for VR Rehabilitation Games: There has been recent research on deriving design guidelines for VR rehabilitation games based on results of empirical studies[Flynn, Lange et al. 2008]. Alankus et al.'s guidelines include: simple games should support multiple methods of user input, calibrate through example motions, ensure that users' motions cover their full range, detect compensatory motion, and let therapists determine difficulty [Alankus, Lazar et al. 2010]. There have been many other guidelines derived [Goude, Björk et al. 2007, Broeren, Bjorkdahl et al. 2008, Burke, McNeill et al. 2009, Burke, McNeill et al. 2009] and there is a need for more focused game design research and development for specific populations [Flores, Tobon et al. 2008].

4.1.3. A Gap in Knowledge

In all of the other VR rehabilitation, the effects of cybersickness were minimally explored. It is critical to understand effects of cybersickness on disabled individuals to make more effective VR rehabilitation systems. Based on the previous research it is likely that cybersickness does significantly affect disabled individuals, but the effects and their measurement are unknown.

4.2. Prior NSF Support

IIS-1153229 (PI Quarles), EAGER: Presence and Navigation in Virtual Reality Rehabilitation Games for Mobility Impaired Persons; $232,676; 8/11-8/13: This grant focuses on the impact of presence - the suspension of disbelief in virtual environments – for persons with disabilities and how presence may influence motivation in rehabilitation games. So far, we have published several papers, e.g.,[Guo and Quarles 2012, Guo, Samaraweera et al. 2013] with several more in submission. One of these papers was based on an REU supplement and was published with only the PI and URM undergraduates as authors[Espinoza, Cantu et al. 2013].

Through these investigations of presence, we have found several cases where disabled persons have different factors that affect presence than that of healthy persons. This leads us to investigate the causes for these differences. One potential cause is a difference in susceptibility to cybersickness. Although this NSF supported research does not specifically investigate the effects of cybersickness in VR, it is consistent with the PI's long term goals of understanding how disabled persons experience VR and motivates the investigations in the current proposal.

IIS-1218283 (PI Quarles) HCC: Small: Determining the Effects of Latency in Virtual Reality Physical Rehabilitation; $472,840; 9/12 - 9/15: This grant focuses on determining the effects of latency in VR for persons with disabilities. Latency refers to how quickly a system can respond to user input and potentially has an impact on rehabilitation performance. So far, we have published one paper [Samaraweera, Guo et al. 2013],which was nominated of best paper at a top conference (acceptance rate ~ 18%) and there are several more in submission. This NSF supported research does not specifically investigate the effects of cybersickness in VR. However, cybersickness is assessed as a secondary measure. Specifically, we found that mobility impaired users are more prone to cybersickness than healthy users. Thus, the study results (see *Preliminary Studies)* helped the PI to form the necessary foundations for the hypotheses about cybersickness in this proposal.

4.3. Preliminary Studies

The PI has conducted preliminary studies to investigate how cybersickness in a VE affects MI persons [Samaraweera, Guo et al. 2013]. Although investigating cybersickness was not the main objective of the study, the SSQs administered provide some interesting secondary results that motivate the hypotheses in the proposed research.

Methods *T*he primary objective of the study was to investigate the effects of latency and avatars on MI persons, but here we focus on the cybersickness findings. We performed a mixed design study with a between-subjects factor of user population (healthy vs. MI users). The participants were tasked with walking in a straight line multiple times in both a real environment and a VE that was modeled after the real environment. The within-subjects conditions were the applied latency (real world as a baseline, 75ms, 150ms and 225ms) and avatar (no avatar or full body avatar). Multiple SSQs were administered intermittently.

Results: To analyze the SSQ results within subjects we performed paired Wilcoxon signed rank tests. Although there were no significant differences in a paired Wilcoxon signed rank test in SSQ scales for total severity measure for healthy participants, there was a significant difference in the pre-study SSQ scales being lower than that of post-study SSQ scales of the MI participants (W=15, p=0.048, z=-1.98). Similarly, based on a Mann-Whitney U test, MI persons post study SSQ scales were significantly higher than healthy (W = 10.5, p-value = 0.037). Moreover, there was a significant inverse correlation between self reports of VE realism and SSQ scores for MI users only (r = -.76, p = .04).

Discussion: Due to the significant differences found through the SSQ evaluations administered at the beginning and the end of the study, it is possible that MI participants' gait was impacted by simulator sickness–increased nausea, imbalance, or dizziness–introduced by the higher latencies. Although, previous research has shown that multiple administrations of the SSQ can actually introduce simulator sickness in healthy participants, repeated measured SSQ has not been extensively conducted with MI users. Thus, it is interesting that the SSQ of healthy participants did not elicit significant differences before and after the study, but there were significant differences for MI participants. This may suggest that MI users are more influenced by SSQs and/or potentially more susceptible to simulator sickness. Towards the feasibility of the studies in this proposal, we expect that the results of this preliminary study were due to MI participants' reaction to increased latency. This is supported by literature to the extent that latency has been found to influence cybersickness. However, it is unknown why cybersickness affects persons with disabilities more than healthy users. The PI aims to determine the main factors that contribute to this difference.

4.3.1. The PI's Experiences as a Mobility Impaired Person in VEs

The PI has significant mobility impairments caused by MS. He usually walks with one or two canes and occasionally a uses manual wheelchair or a powered scooter. The PI did not participate in the study, but did test out the environment numerous times before conducting the study and can be considered an expert user in VEs. This experience has fueled the hypotheses throughout this proposal and has produced several novel anecdotal results.

The PI cannot use a fully immersive version of the HMD while walking, due to safety concerns. If his visual periphery is blocked off, the PI will always fall after a couple of steps. However, the PI can use the system when the periphery is not blocked off. Even when his periphery is unblocked, he often looks down at his feet when navigating through the VE, which is not typically the case when he walks in reality.

Physically, his imbalance in VR may be related to deficits in proprioception. The PI often fails a common test of proprioception, called the Romberg test [Khasnis and Gokula 2003], in which he will fall down if he stands with eyes closed for too long and will definitely fall if he tries to walk with his eyes closed. That is, he depends on his visual sense to maintain balance. Many people with neurological disabilities have the same problem.

Similarly, he believes that his cybersickness has increased since developing his disabilities. His increased cybersickness could be related to his proprioceptive deficits, magnified by general postural instability, and/or correlated to his occasional vertigo experienced in the real world. *These personal experiences are in part what have generated questions about how cybersickness in VR affects persons with disabilities.*

5. <u>RESEARCH PLAN</u>

5.1. Aim #1 Determine how disabilities correlate with VR induced cybersickness

5.1.1. Introduction

The causes, effects, and magnitude of cybersickness in disabled persons are unknown. The *objective* of this aim is to determine how disabilities (e.g., a disabled user may occasionally experience vertigo in the real world) contribute to cyber sickness. The *working hypothesis* is: cybersickness will be increased for disabled users and certain SSQ factors will be correlated to certain disability characteristics, such as self reported level of balance problems and vertigo, which are mostly unique to disabled users. Our *approach* to test this hypothesis is to conduct empirical studies in which both healthy and disabled persons navigate through a realistic VE (such as the one from our preliminary studies). They will take an SSQ at the end of each session, which are sufficiently spread apart to minimize the impact of repeated SSQs. The SSQ scores will be compared to the baseline SSQ score taken at least a week before the first session. The *justification* for this approach is: the studies are designed to determine the differences in cybersickness effects between healthy and disabled users and investigate the correlation between disability symptoms and cybersickness symptoms. The *expected outcome* is a better understanding of cybersickness in disabled users, which can potentially be used to effectively assess and predict cybersickness in VR rehabilitation.

5.1.2. Research Design

To understand the effects of VR induced cybersickness on disabled persons, we aim conduct an empirical study. To make this applicable to VR rehabilitation, the study tasks will be based on exercises typically performed in physical therapy for populations with balance deficits.

5.1.2.1. Independent Variables

Disability (e.g., Healthy, Cane User, Wheelchair User): The goal is to understand what correlations exist between disabilities and cybersickness effects. Thus, the main independent variable here is disability type and severity from several populations. Initially, we will focus our efforts on recruiting healthy users, cane users, and wheelchair users. We will implement selection criteria that keep the populations as homogeneous as possible. Thus, these participants will be screened to eliminate confounding factors such as cognitive/memory deficits. For more information on the screening process and our selection criteria, see *Section 5.5.2 Population, Selection criteria, and screening process.*

Exercise (walking*/rolling, balance)* typical in physical therapy for this population:

1. *Walking/ Rolling* – Cane/Healthy users walk along a straight path, trying to minimize use of assistive devices if needed (e.g., cane), keep good posture, and control gait. Wheelchair users roll along a straight path, trying to keep good posture and speed control.
2. *Balance* – the user tries to maintain balance as they repetitively step on and off of balance pads that are designed to disrupt balance (wheelchair users must be able to stand up and do this as part of the selection criteria).

Reality Level (real, VE): Participants will perform the exercises in both a real environment and a VE modeled after the real environment. Obtaining the data from the real environment will give us an effective baseline to judge performance in the VE.

5.1.2.2. Procedure

This study is a counterbalanced within-subjects study in which the order of conditions will be randomly assigned. We expect that the study will last approximately 3 hours (1 hour per session) and will be spread over three weeks for each participant to minimize the effects of SSQ as a repeated measure. When participants are initially screened, they will be given a baseline SSQ. The first session is primarily for baseline physical assessments - (i.e., gait analysis, reflex test, measure height and weight, heart rate, etc.). Starting in the second session, a different exercise will be performed in each session. Each exercise set will take approximately 1 minute. For one set, users will perform 10 repetitions of the exercise. Each participant will perform 4 sets in each environment (real, VE) (2 exercises * 10 reps * 4 sets * 2 environments = 160 data points per participant). After a session, another SSQ will be administered and participants will also answer a series of other questionnaires to provide subjective feedback.

5.1.2.3. Equipment Used

We will use our VICON MX optical tracking system for full body tracking and the requested NVIS SX166 Head Mounted Display. Participants will use the GaitRite force mat to quantitatively assess gait and balance (i.e., both before and during the exercises in the study).

5.1.2.4. Population, Study Environment, Metrics, Analysis Plan

Since many of these will be the same in all aims, we have consolidated them into section 5.5.

5.1.3. Expected Outcomes

We expect that results will identify the impact of VR induced cybersickness for persons with disabilities, identify disabilities that contribute to cybersickness, and ultimately inform design and implementation of future VR rehabilitation environments.

5.2. *Aim #2 Determine the most effective objective metrics of VR induced cybersickness for disabled persons*

5.2.1. Introduction

It is unknown how to objectively measure cybersickness in disabled persons based on existing techniques (e.g., OKAN) or if there are additional measures unique to disabled persons (e.g., gait changes). The *objective* of this aim is to determine the most effective objective methods of assessing cybersickness for disabled persons. The *working hypothesis* is: quantitative measures such as OKAN [Guo, Ji et al. 2011] will be effective objective measures of cybersickness for disabled persons and performance measures such as gait changes during the VE experience can also be used to detect cybersickness in disabled persons. Our *approach* to test this hypothesis is to conduct empirical studies in which both healthy and disabled persons navigate through a realistic VE (such as the one from our preliminary studies). Their OKAN, gait, and physiological responses will be measured and correlated to their SSQ scores. The *justification* for this approach is: in order to test the effectiveness of objective measures, they must be validated against the generally accepted subjective measure - the SSQ. This approach is what most prior studies of objective cybersickness metrics have done, but were instead focused on healthy participants. The *expected outcome* is that objective measures of cybersickness for disabled persons will be identified, which can potentially be used to detect cybersickness in disabled users earlier and reduce cybersickness during rehabilitation.

5.2.2. Research Design

To understand the effects of VR induced cybersickness on disabled persons and evaluate potential objective metrics, we aim to assess participants' SSQ before and after sessions in a realistic VE, and investigate correlations between OKAN, EEG, gait, physiological measures, and SSQ. To make this applicable to VR rehabilitation, the tasks participants perform will be based on exercises typically performed in physical therapy for populations with balance deficits.

5.2.2.1. Independent Variables

Objective Measure (EOG, EEG, Gait, Heart rate variability, GSR): The primary purpose of this study is to assess the effectiveness of potential objective measures of cybersickness in disabled populations. These measures will then be tested for correlation with the SSQ, similar to the validation of these measures with healthy participants [Kolasinski 1995, Bruck and Watters 2009, Chen, Duann et al. 2010, Guo, Ji et al. 2011].

*Disability (*Healthy, Cane User, Wheelchair User - *same as in aim 1)*

Exercise (Walking/Rolling, Balance - same as in aim 1)

Reality Level (real, VE – same as in aim 1)

5.2.2.2. Procedure

The procedure is almost identical to the procedure in aim 1 - a counterbalanced within-subjects study in which the order of conditions will be randomly assigned, lasting approximately 3 hours (1 hour per session). The main difference is the introduction of the objective metrics conditions, which cannot all be connected at the same time due to do physical constraints (i.e., the EEG and the EOG would overlap some on the participant's head).

5.2.2.3. Equipment Used

We will use the same equipment as in aim 1 but also add in the BIOPAC EOG to assess OKAN, NuAmps EEG to assess brain signals, a Bioharness BT and BodyMedia armband to measure physiological response, such as heart rate, skin temperature, breath rate and galvanic skin response. There may be issues that arise with using the HMD in conjunction with the EEG. If so, we will use a projected display that the PI already has (see *Facilities*).

5.2.2.4. Population, Study Environment, Metrics, Analysis Plan

Since many of these will be the same in all aims, we have consolidated them into section 5.5.

5.2.3. Expected Outcomes

We expect that results will identify the most effective objective measures of VR induced cybersickness for persons with disabilities. This will help to more objectively predict and assess cybersickness in VR rehabilitation, and will enable effective design and implementation of future VR rehabilitation environments.

5.3. Aim #3: Determine the main contributing VE Design factors that affect cybersickness for disabled persons

5.3.1. Introduction

Our preliminary studies suggest that cybersickness may be magnified in disabled persons. However, the main VE design aspects that contribute to this magnification in disabled persons are unknown. The *objective* is to determine these VE aspects. The *working hypothesis* is that the main controllable VE aspects (e.g., *peripheral occlusion, depth cues, FoV*) that may contribute to cybersickness for disabled persons will be the same as healthy persons, but the specific aspects related to balance and "head sway" will magnify cybersickness in disabled persons. Our *approach* to test this hypothesis is to conduct empirical studies with both healthy and disabled persons in which users move in several different configurations of a VE (e.g., with narrow FoV or wide FoV) and cybersickness is assessed in each. The *justification* for this approach is that similarly designed empirical studies have been used to assess the effect of VE aspects on healthy people, but not for disabled people. The *expected outcome* is that we will be able to identify the main contributing VE design aspects that increase cybersickness for disabled users so that VR rehabilitation developers can focus their designs towards reducing cybersickness, which will potentially increase rehabilitation effectiveness.

5.3.2. Research Design

To understand how VE design affects cybersickness for users with disabilities, we aim to compare participants' cybersickness in several VEs, each with slightly different designs.

5.3.2.1. Independent Variables

VE Design Aspect (peripheral occlusion, depth cues, FoV): Motivated by our preliminary data, we will investigate the effects of the following VE aspects on cybersickness in disabled persons. This is based on the fact that disabled persons with balance deficits typically rely more on optical cues to maintain balance, such as:

1. *Peripheral Occlusion* – this refers to whether the real world can be seen in the user's periphery or not. It has been shown that this can have an effect on healthy users' depth perception [Jones, Swan et al. 2013] and cybersickness.
2. *Depth Cues* – This includes shadow, converging lines, and textural detail. Theoretically, increasing depth cues should give the user a more faithful perception of movement. However, many studies with healthy individuals have found that users underestimate depth in VE s[Ponto, Gleicher et al. 2013], which could potentially impact cybersickness.
3. *FoV* – The human FoV is close to 180^{o} but most HMDS have lower FoV, ranging from 35 to 170 degrees. This is known to impact cybersickness in healthy persons, but unknown how this plays a role in disabled persons

*Disability (*Healthy, Cane User, Wheelchair User - same as in aims 1 and 2)

Exercise (Walking/Rolling, Balance - same as in aims 1 and 2)

Reality Level (real, VE - same as in aims 1 and 2)

5.3.2.2. Procedure

The procedure is almost identical to the procedures in aims 1 and 2 - a counterbalanced within-subjects study in which the order of conditions will be randomly assigned, lasting approximately 3 hours (1 hour per session). The main difference is the introduction of the VE Design Aspect conditions. That is, participants will perform the exercises in the VE multiple times with varying conditions of peripheral occlusion, depth cues, and FoV. Each session will focus on assessing the impact of one of these design aspects.

5.3.2.3. Equipment Used

This is the same as in aim 1.

5.3.2.4. Population, Environment, Metrics, Analysis Plan

Since many of these will be the same in all aims, we have consolidated them into section 5.5.

5.3.3. Expected Outcomes

We expect that this study will enable us to identify how the various aspects of VEs contribute to cybersickness in disabled persons. This can be used to inform design and implementation of future immersive VEs for rehabilitation toward the goal of reducing cybersickness.

5.4. Aim #4 Create, disseminate, and maintain an open database of anonymous cybersickness data of disabled persons

Currently, there are datasets of cybersickness SSQ data for healthy individuals[Kennedy, Lane et al. 1993, Brooks, Goodenough et al. 2010], but there is no publically available cybersickness database that includes disabled individuals. Our *approach* is to create and maintain a web-based portal for accessing and adding to this much needed database. We have already been maintaining a similar database internally and will invite all participants from the studies in Aims 1, 2, and 3 to include their data. See the *Data Management Plan* for details and an overview of our proposed human subject protection methods.

The *expected outcome* is similar to that of the existing databases of healthy user's SSQ data. It will reduce the need to perform multiple SSQs for disabled populations and allows post-hoc analysis towards new scientific discoveries about disabled people in the real world and in VEs. We expect that this will help to enable VR rehabilitation designers, researchers, and practitioners to more effectively measure and reduce cybersickness of disabled persons, thereby making VR rehabilitation more effective.

5.5. Shared Research Design Aspects Across All Aims

5.5.1. Motivation for Similar Study Designs

Many of the studies presented are very similar in design (e.g. within subjects, similar independent variables). In fact, they are similar enough that all the aims could probably be conducted as one extremely complex 5 year study. However, combining all the variables into one study would likely cause additional confounds and uncontrolled interactions between variables, thereby reducing the power of the statistical analysis and ultimately limiting our conclusions. Moreover, each proposed study has a unique contribution towards the intellectual merit of this proposal and thus needs to be studied separately.

5.5.2. Populations, Selection Criteria, and Screening Process

In collaboration with the NISA) this study will recruit participants 18 and older from NISA and the southwest Texas area and who are diagnosed with relapsing remitting MS (e.g., there are more than 900 M.S. patients at NISA), have no cognitive impairments, and are in the age range of 40

– 60. Based on the MS Walking Scale (MSWS) (i.e., mobility)[McGuigan and Hutchinson 2004], the Barthel Index (i.e., activities of daily living)[Collin, Wade et al. 1988], and MS Impact scale (MSIS) (i.e., quality of life)[Hobart, Lamping et al. 2001], we will prescreen participants and only include participants who fall within specific ranges (table 2).

We aim to recruit at least 30 MS patients and 30 persons without disabilities per year. Participants will be paid $50 per hour of time and effort. Verbal recruitment from the PI, doctors and physical therapists, e-mail lists, websites, and flyers will be the primary means for recruiting.

Note that we currently have a database of potential participants with at least 40 MS participants who meet these criteria and 35 healthy persons of similar demographics that were gathered in the last year. The PI expects this will grow significantly since he plans to expand his recruiting activities beyond San Antonio and into the greater southwest Texas area through the use of travel funds in this proposal.

Table 2: selection criteria. We propose to perform the studies with several different populations.

Criterion	Single Cane Users	Wheelchair Users	Healthy users
Age	40-60	40-60	40-60
Weight	150-200 lbs	150-200 lbs	150-200 lbs
Height	5’ 2” – 5’11”	5’ 2” – 5’11”	5’ 2” – 5’11”
Cognitive impairment	none	none	none
MSWS	40-60 (moderate)	60-80 (quite a bit)	0 (none)
MSIS	0 – 20 (a little)	40-60 (moderate)	0 (none)
Barthel	80 -100 (a little)	60 - 80 (a little - moderate)	100 (none)

Screening Process: First, we interview every potential participant by phone to verify if the person is qualified for this study and try to keep the participants homogeneous. For example, we ask them some simple questions first, like the year and date (to loosely assess mental faculties) and demographic information. We will not select any person who cannot understand the questions or answer the questions fluently. Those persons, who answer the questions well, are asked to talk more about their physical/mental impairments and major life activities. We also ask them questions about assistive devices required for walking. Then they will take the MSWS, MSIS, and Barthel questionnaires. We also try to ensure that participants are demographically similar across populations. Thus, for each MS person we recruit who meets the stated criteria, we recruit a healthy person of similar age, weight and height. The goal of the screening is to help ensure that participants within each of the three populations are as homogeneous as possible to facilitate effective statistical analyses and minimize study confounds.

5.5.3. Environment

The study will be conducted at the NISA Wellness and Rehabilitation Center in San Antonio. NISA is a physical rehabilitation office with plenty of open space (>600sq ft.). The study will be conducted on at times when the only individuals in the room are the participant and the PI’s team of experimenters. It will be in a quiet air conditioned environment.

5.5.4. Metrics

5.5.4.1. Performance and Physiological

Reflex Speed: (5 trials) participants click the mouse as quickly as possible when told to do so.
EOG: this is used to measure OKAN as an objective measure of cybersickness.
EEG: this is used to measure brain waves to test their relation to cybersickness.

Physiological measures: using the Bioharness BT physiological monitor and the BodyMedia armband, we will measure heart rate, breathing rate, skin temperature, and GSR.

Weight and height: measured at the beginning of the first day.

Gait and Balance: This includes stride length, walking speed, walking phase analysis, and foot pressure distribution. This is performed quantitatively with the GaitRite force platform and associated software and qualitatively with a physical therapist at NISA through video coding.

Exercise specific measures: additionally we will measure exercise completion times and errors.

5.5.4.2. Questionnaires

Disability questionnaire: This will assess disability severity, types, and assistive device use

MSWS: a series of 5-Likert questions that assess walking disability in persons with MS.

MSIS: a series of 5-Likert questions that assess MS impact on quality of life including physical and psychological effects.

Barthel index: a series of 5-Likert questions that assess the impact of disability on activities of daily living, such as getting dressed etc.

SSQ [Kennedy, Lane et al. 1993]: This is the standard approach to measuring cybersickness. It consists of 16 4-Likert scale questions that query issues such as nausea, and dizziness.

Other Questionnaires: 1) subjective comments about the VE, 2) impact of fatigue on everyday activities [Krupp, LaRocca et al. 1989], 3) and computer usage.

5.5.5. Analysis

Descriptive statistics, split-plot ANOVA and Tukey's HSD (for numerical data), and Friedman's test and Wilcoxon signed rank (for ordinal data such as Likert data) will be used to determine significant differences between populations and conditions. Pearson's, Spearman's and Fishers z will be used to analyze correlations. Gait and balance analysis will be performed quantitatively with GaitRite software and qualitatively with physical therapists through video coding using the Gait Abnormality Rating Scale[Russell, Jull et al. 2003].

When enough data has been recorded into the proposed cybersickness database (e.g., over 100 participants) the PI will perform a factor analysis similar to [Kennedy, Lane et al. 1993] to more effectively group and interpret the SSQ data for disabled persons.

5.6. Potential Problems and Alternative Approaches

Working hypotheses invalid: Although our preliminary studies support the potential validity of our working hypotheses, there is an unlikely possibility that that one or more will test invalid. In that case we will consider alternative hypotheses such as: For specific Aim 1: the healthy and disabled participants' relative differences will not be significantly different, but still highly correlated. This will still be an impactful result in that it will suggest persons with disabilities react to cybersickness in a VE similarly to healthy people. The data in our studies will indicate this if it is the case and the data can be mined later to test alternative hypotheses like this. Regardless of the outcome of our working hypotheses, this research will produce interesting data that will provide new insights into VR rehabilitation.

Insufficient number of participants: Based on our preliminary work 30 participants per population for each study is enough to find significance and we expect to be able to recruit that many. However, in the unlikely event that we cannot meet those requirements, we can convert the study to a more longitudinal or single subject design. The procedure for the study would be different (e.g., longer in duration per participant), but it would still effectively test our hypotheses. We expect to determine this in pilot testing, before major resources are expended.

6. TIMELINE (5 YEARS)

AIMS	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5

Aim #1: Determine Impact of disability on Cybersickness	◄────	────►			
Aim #2: Assess Objective metrics for disabled persons' cybersickness		◄────	────	────►	
Aim #3: Identify VE design aspects that contribute to disabled persons' cybersickness				◄────	────►
Aim #4: Create and maintain database of disabled persons' cybersickness data	◄────	────	────	────	────►

7. Broader Impact

7.1. Improving Quality of Life for Mobility Impaired Persons

Physical rehabilitation has a significant impact on the rehabilitation of mobility impaired persons and is standard practice for many types of neurological disabilities. For example, 2.1 million people worldwide have MS [National MS Society 2012]. Many of these people have mobility impairments and go through physical therapy to improve their mobility. Therefore it is extremely important to create effective approaches to rehabilitation and VR potentially has advantages in this area. However, it is imperative to understand how the aspects of VR (i.e., cybersickness) affect the primary population that participates in VR rehabilitation – persons with disabilities - because the effects of cybersickness may have an impact on how users perform exercise, which could affect rehabilitation effectiveness and ultimately quality of life.

Furthermore, if the central hypotheses of this proposal are found to be supported, this work may inspire other researchers in VR to develop approaches to combat cybersickness specifically for disabled persons, which will potentially enable vertical advances in the field.

7.2. Involving Underrepresented Minority (URM) Undergraduates in Research

UTSA is a minority serving institution that continually grows each year. More than 59% of UTSA's undergraduate students come from groups underrepresented in higher education. In fact, many of the undergraduate students that the PI has supervised in research are URM students [Espinoza, Cantu et al. 2013]. The PI proposes to involve undergraduate students in this research (see *Budget Justification*). Getting URM students involved in research is something that the PI is passionate about. Even outside of UTSA, the PI has been involved in outreach (see *Biosketch - synergistic activities*) for inspiring URM middle school student interest in computer science. Also, the PI has obvious disabilities which may inspire disabled students to engage in research. Thus, the PI has unique opportunities to involve and mentor URM students in education and research on the graduate, undergraduate, and elementary school levels. This will increase the diversity of URM researchers in computer science and VR research.

7.3. Community Outreach for Persons with Disabilities

Currently, the PI has been actively visiting and giving invited lectures to local support groups and symposia for disabled persons (see *Synergistic Activities* in the *Biosketch*).These activities help to educate and motivate disabled persons about VR rehabilitation. The PI also uses this as an opportunity to recruit more potential participants in future studies. Thus, these outreach activities are mutually beneficial to the community and to the PI's research.

Through the use of the requested travel and materials funds, the PI plans to significantly broaden his community outreach and participant recruiting efforts. To date, he has mainly focused his efforts on the local San Antonio area. The additional funds from this CAREER proposal would enable him to expand his lecture series to a national level. To facilitate this, the PI will collaborate with various national advocacy societies for persons with disabilities. For example, the PI is already collaborating with the National MS Society (NMSS). The NMSS sponsors all the local MS support groups the PI works with and helped the PI run a participant recruiting booth at the 2013 MS Walk in San Antonio. Ultimately, these broader outreach efforts will not only help the PI increase his study participant population; it will also help to promote education and motivation for VR Rehabilitation research.

8. EDUCATIONAL ACTIVITIES: INTEGRATION OF EDUCATION AND RESEARCH

With the support of the UTSA Computer Science department (see *Departmental Letter*), the PI proposes to develop a new course called *Accessible User Interfaces and Universal Usability*. The PI currently teaches a popular and highly rated User Interfaces and Usability course, but does not have adequate time to cover issues with accessibility and universal usability in depth. This problem in user interface education seems to exist on a national level. There are very few universities that offer a course focused on universal usability, even though there is a wide research community active in this area. Thus, the PI aims to develop this novel course and freely distribute the materials on his website, which will potentially help instructors at other institutions to adopt a course in universal usability.

8.1. Learning Objectives

This course has similar learning objectives to a typical user interfaces course, but is specifically focused on universal usability and accessibility. Thus, objectives focus on a critical understanding of Interface Paradigms and Frameworks, Collection and Interpretation of User Information, Design guidelines, principles and theory, and Evaluating Interface Designs.

8.2. Course Structure

Weekly lectures: The PI will present design guidelines for accessible user interfaces through a series of case studies and instruct students on the specifics of user centered design for universal usability. The PI plans to use the book “Universal Usability: Designing Computer Interfaces for Diverse User Populations” by Jonathan Lazar for student reference.

Research Paper Presentations: The PI aims to foster literature review skills as applied to universal usability. Thus, each student will give two research paper presentations from relevant conferences such as ICDVRAT, ACM ASSETS, ACM UIST, and ACM CHI.

Term Project: In groups, students will design and build an assistive interface for persons with a particular disability. Throughout the semester, students will participate in a user-centered design process where they develop and evaluate an interface to fulfill a specific need of the population they are working with. The groups will be paired with a representative member of a particular disabled population as a stakeholder. These disabled stakeholder volunteers will be recruited from the PI’s IRB approved research subject database. Students will use the stakeholder’s feedback to design, implement, and evaluate a novel accessible interface.

8.3. Course and Teaching Assessment

Anonymous student surveys: The PI conducts his own mid-semester survey to more effectively cater to the learning needs of his particular class. There is also an official university wide course survey at the end of the semester. Together, these two surveys give feedback on teaching effectiveness, workload, and level of difficulty, among many other metrics. The PI will use this information to improve the course.

Project outcomes and feedback: The PI will judge the success of the course based on the effectiveness of the final projects and the feedback from the disabled stakeholders. He will use this information to fine tune future project requirements.

Peer review of teaching: The PI will request teaching evaluations from the UTSA Teaching and Learning Center (http://utsa.edu/tlc/) once per semester. This will enable the PI to improve his approach to teaching and classroom management.