The Use of Technology in Vestibular Rehabilitation and Balance Assessment

by

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Abstract

Background study 1: individuals with vestibular disorders usually complain of dizziness, disorientation, and vertigo in moving visual environments associated with activities such as walking in visually busy environment. Vestibular rehabilitation is considered the clinically accepted intervention for non-surgical vestibular disorders. Part of the intervention is to practice sensory alterations and manipulations that start gradually with one sensory modality then multiple alterations are advised. Habituation exercises using visually provocative stimuli have been shown to be useful during vestibular rehabilitation. Virtual reality based therapy is an emerging technology that can be used in vestibular rehabilitation to provide visual habituation exercises for individuals with vestibular disorders. The purpose of the study was to explore the use of virtual reality based therapy in the treatment of individuals with vestibular disorders.

The first aim in this dissertation was to explore the use of virtual reality based therapy based therapy as an intervention of individuals with vestibular disorders. Methods: Twenty subjects with vestibular disorders participated in the study. All individuals with vestibular disorders underwent virtual reality based therapy vestibular rehabilitation; the dose of the intervention was one time per week for six weeks. To determine the effect of the intervention,

subjects were tested using self-report and performance measures before, one week after the intervention, and at six months follow up. Results demonstrated that the majority of subjects improved on each measure except for the Timed Up and Go and gait speed. The majority of subjects maintained improvements of each measure at six months.

The second aim was to examine the difference in self report and performance measures between virtual reality based therapy and customized physical therapy. Methods: Forty subjects with vestibular disorders participated in the study; subjects were assigned into two groups (virtual reality based therapy or customized physical therapy). Both groups had six treatment sessions for six weeks, and were assessed using self-report and performance measures. Results: both groups improved in most of self-report and performance measures and maintained improvements six months after the intervention ended. Virtual reality based therapy provided similar outcomes for individuals with vestibular disorders when compared with customized physical therapy.

Background study 2: Falling is a risk factor associated with vestibular disorders that can impact quality of life and reduce physical and psychological aspects in participation in daily life. Falling can be caused by a decline in function of sensory inputs associated with aging. Measuring sensory control during standing may help to investigate age and vestibular disease effects on balance. The measurement of postural control during standing has been investigated using low and high tech methods. The recently developed Balance Rehabilitation Unit (BRU™) utilizes high technology in balance assessment. The psychometric properties of the BRU including the reliability and validity (convergent) have not been studied. The purpose of study 2 was to examine the reliability and validity of the BRU in the assessment of people with and without vestibular disorders.

The third aim of this dissertation is to examine the reliability and concurrent validity of the BRU compared with the Sensory Organization Test (SOT) and to examine its ability to discriminate among healthy people and people with vestibular disorders. Methods: Ninety subjects (30 young healthy, 30 older healthy over 60 years of age, 15 young individuals with vestibular disorders (< 60 years of age), and 15 older individuals with vestibular disorders over the age of 60) participated in this study. Results: The BRU provided a reliable and valid measure for measuring the sensory contributions to postural control for healthy persons and people with vestibular disorders. The BRU and SOT provide similar results related to age and disease effect on sway measures during quiet standing.

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PREFACE

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1.0 INTRODUCTION

1.1 THE USE OF VIRTUAL REALITY BASED THERAPY IN VESTIBULAR REHABILITATION

Individuals with vestibular disorders usually complain about dizziness, vertigo, balance problems, and falls.[1] They usually complain of blurred vision with activities requiring head movements while walking such as looking for products in shopping malls or reading signs while driving.[1] Individuals with vestibular disorders report increased symptoms in visually complex environments and demonstrate increased sway when exposed to full-field visual motion, possibly because they become more dependent on information from non-vestibular systems, particularly vision.[2-6]

Symptoms resulting from vestibular disorders impact activities that require postural control such as standing and ambulation in different environments, and unwanted consequences may result from poor postural control such as a fall.[7, 8] Sensory disturbances and motor impairments resulting from vestibular disorders lead to disruptions in activities of daily living (ADL) and quality of life.[9, 10]

During treatment of individuals with vestibular disorders, part of the intervention for postural control disorders is to practice exercises that promote visual-vestibular and/or somatosensory-vestibular conflict.[11-13] Visual information can be altered by asking subjects to perform exercises in visually busy environment, in poorly lit environment, or with full background visual fields. Difficulty of the training is increased gradually by adding vestibular stimulation such as incorporating head movements.[11-13]

Virtual reality based therapy may be an ideal way to provide habituation exercises for individuals with vestibular disorders who become symptomatic in complex visual environments. Several groups have used provocative visual stimulation to enhance vestibular adaptation and habituation in people with vestibular disorders. Viirre (2002) used visual displays as an incremental adaptation protocol in an experiment with subjects with low VOR gain and found that VOR gain increased significantly after the experience compared to the control group with head movement exercises without the visual display.[14] Pavlou (2004) reported significant improvement in posturography scores and visual vertigo symptoms in individuals with vestibular disorders after the use of desensitization exposure to optokinetic visual stimulation with whole body or surround rotation as a habituation tool.[15]

Virtual reality based therapy using the Balance Near Automatic Virtual reality based therapy Device (BNAVE), grocery store version, may provide good method for visual habituation training for individuals with vestibular disorders since the healthcare provider can control the amount and intensity of the visual stimuli according to the individual situation and progress. The VRBT may help individuals with vestibular disorders to lessen hypersensitivity to visual and motion stimuli, reduce the avoidance of certain activities, and progress their self confidence. Habituation exercises are one method to decrease space and motion sensitivity and to decrease the dependence on one type of sensory feedback for postural control.

1.1.1 Statement of problem

Individuals with vestibular disorders report increased symptoms in visually complex environments and demonstrate increased sway when exposed to full-field visual motion that impact activities that require postural control such as standing and ambulation in different environments and lead to disruptions in activities of daily living (ADL) and quality of life. One of the treatment methods used to treat individual with vestibular disorders is through the use of habituation exercises; visually provocative habituation exercises have been shown to be useful during vestibular rehabilitation. Virtual reality based therapy (VRBT) may be an ideal way to provide visually provocative habituation exercises for individuals with vestibular disorders who become symptomatic in complex visual environments. We investigated the use of VRBT in the rehabilitation of individuals with vestibular disorders to facilitate desensitization of symptoms increased in visually complex environment.

1.1.2 The purpose

The first specific aim was to examine the use of virtual reality based therapy as an intervention for individuals with vestibular disorders. The study examined the effect of a VRBT intervention on self report measures and performance measures to determine the immediate and long term (6 months) effect of VRBT on gait, balance, nausea, headache, dizziness and visual blurring symptoms.

The second specific aim was to determine the difference in self report and performance measures between conventional therapy and therapy in the Balance Near Automatic Virtual reality based therapy Device (VRBT) in persons with vestibular disorders.

1.2 PSYCHOMETRIC PROPERTIES OF THE BALANCE REHABILITATION UNIT ASSESSMENT MODULE OF SENSORY CONTROL DURING STANDING

Postural control can be described as the ability to control body position in space in different environments that require different tasks. Postural control is essential in every task performed, postural control is important in activities like sitting, standing, walking, and running performed in different environments.

The CNS must organize sensory information from visual, somatosensory, and vestibular systems to have an accurate picture of postural orientation and to know when and how to generate appropriate movement strategies for controlling balance in space.[16, 17] Sensory information from vision provides important information to the CNS concerning the position and motion of the body relative to the environment. Information to the CNS about body position and movement in space relative to the support surface is provided by the somatosensory system. Information to the CNS about movement and acceleration of the head in space is provided by the vestibular system.

Quiet stance is associated with small amounts of sway that help the body to maintain equilibrium, the backward and forward sway during standing provide feedback information to the nervous system about postural orientation and help the body to maintain equilibrium.[18, 19] Center of pressure sway magnitude may increase when exposed to accurate vs. inaccurate visual information. Center of pressure sway magnitude may differ when standing in different support surfaces that provide accurate vs. inaccurate somatosensory information. Center of pressure sway magnitude may differ among persons with or without intact vestibular information.[20]

Aging is an important factor that influences postural control. A decline in function of multisensory inputs including somatosensory system, visual system, and vestibular system are associated with aging.[21, 22] Falls rates among elderly people are at least 33% per year, and considered the seventh most cause of death in people over 60 years.[23, 24] Measuring postural control among different age groups may help to investigate age effect on balance.

Measuring postural control may help to differentiate between individuals with sensory conflict/over reliance and/or sensory selection problems for balance control. Subjects who are more likely to have inter-sensory conflict are more likely to have limited ability to organize sensory information.[25]

Examining balance in the 6 conditions of the sensory organization test (SOT) provides insights into the persons' ability to organize and select sensory information appropriate for balance which may demonstrate the type of environments and tasks responsible for imbalance.[25] The Balance Rehabilitation Unit is a new measure for balance that uses Head Mounted Display and foam as part of the balance assessment and can measure balance in the same conditions used with Sensory Organization Test. The Balance Rehabilitation Unit requires less space and is considered less expensive. The balance assessment module in the Balance Rehabilitation Unit might be used as an objective balance assessment modality for people with/without vestibular disorders. The psychometric properties of the BRU are important to be established in order for the device to be useful. The reliability and validity of the BRU are the main psychometric properties to be examined. The Balance Rehabilitation Unit device will be compared to the

Sensory Organization Test in healthy (young, older) and individuals with vestibular and balance disorders.

1.2.1 Statement of problem

There is clear evidence of aging effect and vestibular disorders effect on balance. The BRU is a new device that has an assessment module of sensory control during standing. It uses foam and a head mounted display to provide inaccurate somatosensory and visual sway referenced feedback during standing. Psychometric properties including reliability and validity have not been established for the BRU.

1.2.2 The purpose

The purpose of this study was to examine the reliability (test retest) and convergent validity of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders compared with a standard objective measure of balance, the Sensory Organization Test.

1.2.2.1 Specific aims

Aim 3: To examine the test-retest reliability of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders by examining balance twice in every subject.

Aim 4: To examine the convergent validity of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders by comparing the results of the Balance Rehabilitation Unit with the results of the Sensory Organization test.

Aim 5: To examine group differences among the study groups (young healthy vs. old healthy vs. individuals with vestibular disorders) in the BRU and CDP six balance conditions.

2.0 BACKGROUND AND SIGNIFICANCE

2.1 PREVALENCE OF VESTIBULAR DISORDERS

Individuals with vestibular disorders usually complain about dizziness, vertigo, balance problems, and falls.[1] Prevalence studies have shown that 20% to 30% of the general population have complaints of dizziness.[26, 27] The life time prevalence of vertigo resulting from vestibular dysfunction among adults within the age range 20-79 years is 29%, and the one year incidence of vertigo is 3.1 %.[28] Females have a higher vertigo prevalence than males with a ratio of 2.7:1 (female to male one year prevalence).[28] Vertigo has a high recurrence rate of 88% and has a negative impact on patients' life.[28] Forty percent of the affected individuals had interrupted daily activities, 41% had sick leave, and 19% avoided leaving the house because of their vertigo.[28] Vestibular disorders may be the main intrinsic factor leading to incidents of falling among the elderly; among 546 incidents of falling that resulted in a visit to an emergency department, 80% had vestibular impairments and 40% were complaining of vertigo.[10] The incidence of falls among individual s with bilateral vestibular loss (51%) is significantly higher than the incidence of falls in the general population (25%) in people between 30-80 years of age.[29] A cost study shows that 1 of 10 falls results in serious injuries for the elderly and requires hospitalization; the average cost for the hospitalization is 11,800 US dollars.[30]

2.2 THE EFFECT OF VESTIBULAR DISORDERS ON QUALITY OF LIFE

The quality of life (QoL) of individuals with vestibular disorders can be reduced and their participation in daily life activities can be restrained due to physical, psychological, and cognitive deficits resulting from their vestibular disorders.[29, 31] Dizziness, blurred vision, and poor postural control resulted from vestibular disorders negatively impact activities that require postural control such as standing and ambulation in different environments, and unwanted consequences may result from poor postural control such as a fall.[7, 8] Sensory disturbances and motor impairments resulting from vestibular disorders lead to disruptions in activities of daily living (ADL) and quality of life.[9, 10] Normal processing of visual, vestibular, and somatosensory afferent inputs provide correct spatial orientation and adaptive eye and body movement which produce clear vision during head movement and sustained balance. Abnormal central processing due to vestibular dysfunction leads to dizziness or vertigo, balance difficulties, and blurred vision that cause interruptions in ADLs, cognitive impairments, and associated anxiety symptoms.[10] Recognizing symptoms alone may not be enough for understanding associated functional impairments since it is highly influenced by the individual's nature and needs.[32, 33] The patient's rating of their symptoms is critical for determining their level of disablement; individuals with vestibular disorders rate themselves as functionally disabled in many skills and having reduced quality of life. [32, 34]

Studying disability associated with peripheral, central, or mixed vestibular disorders assists in the understanding of the impact of vestibular disorders related to quality of life and ADLs.[35] Benign Paroxysmal Positional Vertigo (BPPV) is one example of a vestibular disorder that affects quality of life. Individuals with BPPV complain of episodes of vertigo associated with changes in head position that may limit their ADL.[36] People with BPPV have reduced quality of life and ADLs associated with their disease including: 1) difficulty sleeping, 2) discomfort and reduced independence, 3) an inability to work, and 4) some have severe impact on major occupational life roles such as difficulty making the bed or doing chores that require bending.[9, 37]

Another example of how vestibular disorders affect quality of life is reflected in individuals with Meniere's disease. They complain of sudden vertigo attacks that come and go, sometimes leading to a constant low level of discomfort and fear during and after the episodes.[31] They complain of disrupted and discontinued activities at home, work, and social life.[38] They reported moderate to severe handicap in emotional and physical activities associated with the disease using the Dizziness Handicap Inventory.[39] Decreased quality of life associated with Meniere's disease can be explained by the functional limitations resulting from vertigo plus the emotional and psychological problems associated with the hearing problems.[31] Studies reported various quality of life limitations associated with vestibular dysfunction including difficulty walking in dark places (23-46%),[40] reduced life satisfaction at work and leisure time and less participation social activities,[38] difficulty using a telephone and other activities that require good hearing,[41] and difficulty in driving.[41]

Individuals with chronic vestibular diseases due to unilateral vestibular weakness, vestibular neuronitis or labyrinthitis have chronic vertigo that affects their ADLs and decreases their level of independence.[42] Patients have limitations in activities inside and outside the house, including home management, walking in and outside the house, participation in social events, difficulty driving in traffic, and difficulty driving in visually degraded environments.[9, 32, 43]

Bilateral vestibular disorders (BVD) provide another example for how vestibular disorders disturb quality of life. Disability associated with BVD can be explained by two factors affecting ADLs: oscillopsia and poor balance control.[44] Individuals with BVD have difficulty reading signs in the street while driving or walking and sometimes recognizing people while walking.[45, 46] People with BVD are at high risk of falling, are handicapped because of oscillopsia, have difficulty in the shower, and have difficulty walking on uneven surfaces and in low light environments.[44]

2.3 SIGNS AND SYMPTOMS OF VESTIBULAR DISORDERS

2.3.1 Description of dizziness

Dizziness is one of the most common complaints to physicians in the United States, responsible for over 8 million medical visits per year.[47] It has been used as a general term to describe many sensations including light-headedness, being off-balance, vertigo, presyncope, and various other symptoms. Decreased blood flow to the brain resulting from some pharmacological side effects or cardiovascular problems can lead to the sensation of light-headedness. Symptoms associated with fainting episodes including constricted vision, shortness of breath, a cold feeling or sweating can best describe light-headedness.[47] Finally, individuals with inner ear problems often report vertigo symptoms. Fifty four percent of dizziness reported in primary care is classified as vertigo.[35] Vertigo is a feeling of spinning either of self or movement of the surrounding.[47]

Dizziness can result from disorders that can be assigned a specific diagnosis due to peripheral vestibular lesions including bilateral vestibular loss, vestibular neuritis, Meniere's disease, and BPPV; and disorders due to central vestibular lesions such as migraine-associated dizziness, vertebro-basilar insufficiency, and dizziness after head trauma.[48] Symptoms seen in individuals with peripheral vestibular loss other than what has been described in the prevalence section for specific diagnoses include dizziness, oscillopsia, and balance dysfunction. Individuals with unilateral and bilateral vestibular loss complain of dizziness that usually increases when the person is moving and decreases while sitting and lying down. The decreases in vestibular function result in reduction in visual acuity during motion with individuals often complaining of visual blurring. With oscillopsia, patients see objects jumping; symptoms increase during walking and with head movements which affects the person's ability to recognize people while walking, reading street signs while driving, and finding objects while shopping. Individuals with bilateral or unilateral vestibular loss often have problems with their balance during standing, walking, and sitting down or lying down in the acute stage. Balance problems may be a long term problem since presently there is no long term substitution for vestibular function. Central disorders such as migraine associated dizziness is a quite common form of central dizziness among the population with a 6.5% one year prevalence.[48] Individuals complain of dizziness with or without headache.[48] Vertebro-basilar insufficiency caused by an ischemic attack in the posterior circulation can affect the labyrinth resulting in dizziness and imbalance.[48] Individuals who had head trauma report dizziness that is non clearly described and nonspecific; they report floating or dizziness with no vertigo symptoms.[48, 49]

2.3.2 Common causes of dizziness

Dizziness resulting from inner ear problems can be caused by various conditions with different symptoms and can be classified based on the location of the dysfunction (peripheral, central, or mixed). Benign paroxysmal positional vertigo (BPPV) is one cause of vertigo that is triggered by head movement during turning in bed or changing head positions relative to gravity that lasts for seconds to minutes. BPPV occurs when otoconia float free in the semicircular canals.[50] Meniere's disease can cause vertigo attacks that lasts minutes to days associated with tinnitus, impaired hearing, and disequilibrium between attacks.[51] Finally, another factor associated with the occurrence of dizziness is migraine. Migraine associated dizziness is common, with two third of individuals with migraine complaining of vertigo and dizziness.[52] Viral infections can cause vestibular hypo-function and manifest as peripheral disorders such as neuronitis. Individuals are vertiginous, nauseous and experience emesis but have intact hearing.[47, 53] Pathologies affecting all three sensory channels (vision, vestibular system, and somatosensory), reported mostly in the elderly, lead to multisensory dizziness and is manifested as unsteadiness and balance dysfunction.[54] Dizziness is often associated with many neurological disorders including stroke, migraine, infections in the nervous system, inflammatory diseases, tumors and other neurological causes.[47]

2.3.3 Dizziness: a common symptom in balance disorders and psychiatric disorders

Some individuals with both psychological and vestibular disorders describe dizziness as their chief complaint. Anxiety and psychiatric disorders are common in individuals with vestibular disorders, and also vestibular disorders are common among individuals with psychiatric disorders.[49, 55] The presence of one of them does not rule out the presence of the other one.[55] Light-headedness is common in individuals with vestibular and psychiatric disorders and can result from hyperventilation; individuals report symptoms of spinning during and between attacks.[48]

Dizziness can be confounded with anxiety and psychological disorders. Individuals may describe subjective symptoms of non-specific light-headedness associated with imbalance.

Individuals may report an increase in their symptoms in crowded places with a visually rich environment.[56-58] Key clinical features may include physical neuro-otologic symptoms including head fullness, unsteadiness, and being more prone to swaying and developing visual or surface dependence since they are highly sensitive to visual and proprioceptive stimuli, particularly in busy and complex environments.[56, 58]

Since anxiety is associated with vestibular disorders, a two-step diagnosis process is used to examine balance and psychiatric disorders, especially in cases simulating chronic subjective dizziness accompanied with anxiety.[59] Physical neuro-otologic symptoms are described, then in the second step psychiatric symptoms are investigated. Psychiatric associated symptoms may include: panic attacks that could occur in individuals with or without vestibular disorders, anticipatory anxiety that indicates early worry of activities associated with dizziness, and phobic avoidance that include the avoidance of positions or places because of fear of the dizziness consequences.[56]

2.3.4 The interface between dizziness and anxiety

Several large case series have elucidated the clinical characteristics of vestibular disorders.[56, 60] People with vestibular disorders usually complain of anxiety (general anxiety and/ or persistent agoraphobic symptoms).[55] A questionnaire based study was conducted in over 2,000 random individuals in outpatient clinics; 20% had dizziness during the preceding month and 50% reported anxiety and avoidance behaviors.[27] Individuals with both balance disorders and anxiety report increased symptoms in visually complex environments including space phobia, supermarket syndrome, height and visual vertigo.[2, 4, 5] Individuals with vestibular disorders may demonstrate increased sway when exposed to full field visual motion if they become more dependent on information from non-vestibular systems, particularly vision.[61]

One way to understand the relationship between anxiety and vestibular disorders is that dizziness and anxiety factors can exacerbate each other.[62] Psychiatric symptoms may appear as somatic vestibular symptoms and severe dizziness may affect the psychiatric defense negatively when the individual develops fear and avoidance symptoms of positions and environments associated with their dizziness, which may lead to chronic dizziness.[63] However, the explanation that anxiety and dizziness enhance the chronicity of each other depends on the individual's ability to cope with dizziness; symptoms of anxiety are more likely to develop in those prone to anxiety due to previous history or social conditions.[64]

Somatopsychic effects start when the individual develops severe vestibular symptoms that cause the individual to fear vestibular symptoms and consequently develop panic attacks even with less severe vestibular symptoms. They are also prone to develop agoraphobia and avoid situations because vestibular symptoms usually are aggravated in certain environments and situations, including visually complex environments.[48]

Psychosomatic symptoms are the other aspect that can explain the interface between anxiety and dizziness. Psychiatric disorders can lead to the occurrence and/or the enhancement of vestibular symptoms.[65] Cognitive and behavioral means as one form of psychosomatic processes is used in vestibular rehabilitation and can explain the interface between anxiety and vestibular symptoms. Dizziness triggered by head movement is translated as warning behaviors that lead to balance dysfunction. Vestibular rehabilitation that includes repeated head movements or an exposure to visually complex environment that aggravate dizziness with the intention of encouraging central tuning and recalibration can be considered as a behavioral form of intervention that teaches the individual to know the causes of dizziness and also to control and cope psychologically and systemically with the aggravating factors.[65-67]

Psycho-physiological means as another form of psychosomatic processes can also explain the interface between anxiety and vestibular symptoms. Anxiety arousal is strongly associated with an increase in autonomic symptoms, which in turn promotes self-restriction activities especially in visually complex environments, that may lead to higher levels of handicap and prolongs recovery time.[31, 52] Knowing that anxiety arousal is associated with hyperventilation, and that hyperventilation has been shown to unmask vestibular disorders,[68] this process may explain the psycho-physiologic effect of anxiety on dizziness and other vestibular symptoms. Hyperventilation engenders and provokes somatic symptoms which in turn inspires self-restriction activities and increases the handicap resulting from dizziness.[54, 69, 70]

The psychosomatic influence can also be explained by the role of attention and cognitive tasks on postural control. The impact of attention and cognitive tasks on postural control has been studied in dual tasks studies that examine the execution of diverse mental activities while performing balance tasks.[71, 72] Cognitive tasks that require attention include memory tasks and complex orientation activities such as reading road signs while driving and looking for products while shopping in visually complex supermarkets. Studies show that individuals with vestibular disorders have difficulty performing advanced balance tasks when combined with cognitive tasks.[65, 73] Cognitive and complex orientation tasks increase dizziness in individuals with vestibular disorders.[65, 73] Activities that require a high level of attention cause a high level of competition on cortical spatial processing which may affect the processing capacity required for orientation in space while performing balance activities, leading to reduction in either the cognitive task or balance task.[65, 73] Cognitive and complex orientation tasks in visually complex environments may be useful in the intervention of individuals with vestibular disorders.

2.3.5 Symptoms resulting from vestibular/ vision/ somatosensory mismatch

To understand the mechanism of dizziness resulting from vestibular/ visual/ somatosensory mismatch during balance assessment and vestibular rehabilitation, one should understand the three systems responsible for postural control. Sensory inputs from vision, somatosensory, and vestibular systems are integrated together and processed in the central nervous system to control balance. A mismatch between information from these three systems can cause balance dysfunction and dizziness. Individuals with vestibular disorders who up-weight information from somatosensory channels are called surface dependent. Persons who are surface dependent may have more sway during standing and reduced balance control in situations with the support surface unstable. Individuals with vestibular disorders who up-weight information from vision over vestibular information are called visually dependent and may have sway during standing and reduced balance control when exposed to complex visual scenes.[49]

Competition among the three sensory systems, during balance assessment and vestibular rehabilitation, challenges postural control and compels the central nervous system to process the integrated information to determine the correct positioning and alignment in space.[74] Information from the eyes can be used to ascertain and distinguish between movement of the surround and movement of the body; unsteadiness and disequilibrium may take place in situations when the eyes are unable to distinguish between self-motion and movement of the surround.[75] Peripheral and central visual fields are sensitive to moving visual scenes and engender postural sway, with the peripheral visual field being more stimulated by moving visual stimuli and stimulating body sway.[76] The amount of sway associated with visual stimuli, during balance assessment and vestibular rehabilitation, is affected by the frequency of the moving scene and the features of the moving scene, including the quantity and quality of the visual environment.[77, 78]

2.3.5.1 Space and motion sensitivity, discomfort, phobia, and visual vertigo with challenging conditions

Conflict and contradiction among the three sensory channels is most likely condition specific, and occurs in situations that are challenging for the balance system (vision or somatosensory) in situations that require the vestibular system to be intact for good postural control. Sensory mismatch occurs when the vestibular system provides information that disagrees with the information from the other two systems or when there is a mismatch between vision and somatosensory.[48] Symptoms of height vertigo, increased body sway, and dizziness can occur in a healthy individual in challenging conditions that require intact function of the three sensory channels when there is information reduction from any of the channels.[2, 79] A reduction of sensory information in a challenging condition may lead to a mismatch among the sensory channels and produce space and motion sensitivity for the conditions that cause the mismatch.[2, 79]

Individuals with vestibular disorders may become space and motion sensitive when exposed to somatosensory or visual challenging conditions.[48] Space and motion sensitivity in individuals with balance disorders is displayed as increased body sway in challenging conditions that provide confusing sensory information for balance.[48] Since space and motion sensitivity in individuals with balance disorders is situationally specific, if not treated, individuals may develop space and motion discomfort or visual vertigo that are triggered by complex visual environment such as shopping malls.[48] Studies show that space and motion discomfort symptoms have been recognized in both individuals with balance disorders and anxiety disorders.[80] However, the consequence of space and motion discomfort may become critical and affect quality of life and activities of daily living and participation when the individual avoids behaviors that incite symptoms. Such avoiding behaviors are the consequence of having space and motion discomfort as a symptom that may develop into space and motion phobia.[48]

Visuo-vestibular mismatch may also produce symptoms called visual vertigo in individuals with vestibular disorders.[81, 82] Visual vertigo is prompted by visual stimuli in specific visual environments and the individuals' symptoms are of a vestibular nature. Individuals show symptoms of disorientation, dizziness, and vertigo in moving visual environments like driving in traffic, walking in crowds, and walking in busy environments such as supermarkets.[81] Individuals who can be classified as visually dependent in postural control (i.e. individuals who show increased sway when exposed to visual stimuli) and have a vestibular disorder may develop visual vertigo.[81, 83] The goal of treatment for those individuals is to promote desensitization and tolerance to the triggering stimuli.[82]

2.4 VESTIBULAR REHABILITATION FOR VESTIBULAR DISORDERS

2.4.1 Efficacy of vestibular rehabilitation

Vestibular rehabilitation provided by physical and occupational therapists is now considered to be an accepted intervention for individuals with inner ear disorders. Vestibular rehabilitation is the recommended intervention for individuals with gait and balance disorders by the American Academy of Orthopedic Surgery and the American Geriatric Society.[84, 85] Quality of life and participation in daily activities has shown to be significantly improved in individuals with vestibular disorders after vestibular rehabilitation.[34, 86, 87]

Standard vestibular rehabilitation programs consist of a set of exercises that encourage sensory compensation or vestibulo-spinal and vestibular ocular reflex adaptation. For vestibulo-ocular reflex adaptation, the individual is encouraged to practice repeated eye-head movements to promote retinal slip.[88] Vestibular rehabilitation also includes strategies for improving balance and reducing anxiety.[88]

Studies have shown that vestibular rehabilitation is an effective intervention for reducing vertigo and dizziness symptoms and improving balance and physical functioning.[89] Cohen determined that subjects with labyrinthine lesions displayed significant improvements after vestibular rehabilitation and showed reduced levels of disability and enhanced independence in activities of daily living.[34] Yardley et al. investigated the effectiveness of vestibular rehabilitation in a randomized controlled trial for individuals with inner ear disorders. Subjective self report measures showed reduction in symptoms of vertigo, dizziness, and discomfort; functional measures showed significant improvements in balance.[29]

Mira et al. studied the effect of vestibular rehabilitation on quality of life for individuals with vestibular disorders and compared that with medication care. After 3 months of rehabilitation, subjects receiving vestibular rehabilitation had improved significantly compared to the medication group and subjects maintained improvement at 6 months follow up. Vestibular rehabilitation had a significant positive influence on postural control and reduced handicap related to dizziness.[29]

Also studies by Horak et al.[90], Keimet al.[91], and Telian et al.[92] used measures for self assessment including ADLs, questionnaires and functional performance for balance, gait, and posturography to study the efficacy of vestibular rehabilitation. The majority of subjects improved significantly in their symptoms after the intervention. Horak et al. compared vestibular rehabilitation intervention that included balance training and head movement exercises compared to a medication group and found that subjects in the vestibular rehab group had enhanced improvement in postural control.[90]

Cohen et al. reported on individuals with chronic peripheral vestibular disorders who were treated for 6 weeks with a program that included head movement exercises at home or during biweekly outpatient sessions.[93] Subjects' vertigo symptoms were reduced over the treatment period; balance and functional gait outcomes improved and the important factor believed to influence improvement was the combination of repetitive head movement with the gradual increases in movement speed and visual/vestibular interaction.

Yardley et al. also investigated the effect of a 6 weeks vestibular rehabilitation program that included a head body movement exercise and relaxation program on subjects with vertigo and balance disabilities resulting from inner ear disorders. Symptoms of vertigo and anxiety lessened significantly in the vestibular rehab group and balance skills abilities improved after the rehabilitation program.[94]

Cohen et al. studied the effect of a vestibular rehabilitation program on activities of daily living, psychosocial and functional activities after treating dizziness and vertigo. They found that the reduction of vertigo after the rehabilitation program lead to improvements in activities of daily living and participation in psychosocial activities. Home management, self-care management and occupational management were improved.[42] Cowand et al. investigated the effect of a vestibular rehabilitation program using self-report and performance measures among three groups: individuals with peripheral vestibular lesions, central vestibular lesions, and mixed vestibular lesions. The intervention program included balance training, head movement exercises, gaze stabilization exercises, motor coordination exercises, and a home program. Seventy eight percent of all groups improved in the Dizziness Handicap Inventory in the physical and functional subscales.[95]

Studies have investigated the impact of vestibular rehabilitation on reducing the risk of falling in individuals with vestibular disorders using falls assessments and prediction measures such as the Dynamic Gait Index, the Timed Up and Go, and gait speed. Macias et al.[96] , Brown et al.[44], Wrisley et al.[97] , Whitney et al.[98] , and Herdman et al.[12] found that vestibular rehabilitation is able to reduce the risk of falls in individuals with inner ear disorders and has a positive impact on both subjective and objective measures of balance.

Several studies have investigated the impact of vestibular rehabilitation in individuals with unilateral and bilateral vestibular dysfunction. Vestibular ocular reflex gain and dynamic visual acuity improves significantly after vestibular rehabilitation.[99, 100] Badke et al.[101], Horak et al.[90], and Yardley et al.[94] reported improvement in dynamic visual acuity, postural stability, and subjective symptoms of dizziness and vertigo for individuals with acute or chronic peripheral vestibular hypofunction. Other studies have investigated the impact of vestibular rehabilitation on postural control and locomotion stability for young and older individuals with vestibular disorders using Sensory Organization test, gait, and balance assessment measures. Most studies report an increase in the ability of individuals to control balance and stability after vestibular rehabilitation.[97, 98, 101]

2.4.1.1 Appropriate individuals for vestibular rehabilitation

Vestibular rehabilitation is optimal for individuals with stable non-fluctuating unilateral or bilateral vestibular lesions with partial central compensation.[13] After a vestibular lesion, acute compensation immediately occurs within the first 3 days that controls symptoms of nausea, vertigo, poor gaze stability, and space and motion discomfort. The acute compensation produces a more symmetrical firing rate at the vestibular nuclei under the inhibition influence of the cerebellum.[102] Individuals with incomplete acute compensation are good candidates for vestibular rehabilitation compensation intervention.[13] However, individuals with unstable symptoms that occur spontaneously such as central vestibular disorders or Meniere's disease may not benefit significantly from vestibular rehabilitation, but they can be educated about their symptoms and provided with strategies to manage their vestibular disorders.[13]

Individuals with unilateral vestibular loss usually complain of blurred vision and oscillopsia that is called gaze instability with activities requiring head movements while walking such as looking for products in shopping malls or reading signs while driving or walking. Persons with unilateral loss may also complain of space and motion sensitivity in certain busy environments such as supermarkets and train stations manifested as dizziness, disequilibrium, or blurred vision. Complaints of dizziness related to head movement are common. Postural instability and disequilibrium are other complaints of individuals with unilateral vestibular disorders.[13] The aims and strategies of physical therapy interventions are focused to improve the symptoms and reduce the impairments.

Individuals with bilateral vestibular loss have impairments affecting postural control, instability, and gait disturbances especially in visually degraded environments and/or somatosensory disturbing surfaces since individuals with bilateral vestibular loss tend to be vision dependent or somatosensory dependent.[103] Individuals with bilateral vestibular loss also have oscillopsia (visual blurring) that becomes worse in dark environments with head movements.[103] Individuals need to develop strategies to help hold the image of the object fixed on the fovea with head movements.

In individuals with vestibular disorders, information from the vestibular system is distorted or reduced and the individual becomes more dependent on information from their vision and/or proprioception systems.[104] Somatosensory information to the CNS provides essential input about stability, body sway, position in space, and motion of body segments. Sensory information from the upper limbs, lower limbs, trunk, and neck are important and influence postural control. Inputs from the hand through various surfaces (rails, walls, or cane) can enhance postural control. Sway increases in normal and individuals with inner ear disorders when sensory information from the ankle during standing or walking is reduced through surface perturbations. Normal subjects have the ability to perform head and neck counter-rotation in stationary or motion tasks; subjects with inner ear disorders practice compensatory strategies to reduce their symptoms that sometimes work against their rehabilitation such as head locked on trunk movements where they reduce neck movement.[104]

Studies show that visual information is important when the somatosensory information or the vestibular information is absent or disturbed.[3, 6] Subjects with inner ear disorders have more sway when asked to close their eyes with or without sway reference disturbance; the incidence of falls increased when the subjects are asked to close their eyes while standing.[3, 6] The importance of visual information increases when both somatosensory and vestibular systems are impaired.[105]

During treatment of individuals with vestibular disorders, part of the intervention for postural control disorders is to practice visual-vestibular and/or somatosensory-vestibular alterations.[11-13] Manipulation of sensory information should start gradually with one sensory modality, then multiple sensory alterations are advised. Visual information can be altered in the intervention by asking subjects to close their eyes and move their head side to side or in the vertical plane; subjects may be asked to perform exercises in busy environment, in poorly lit environment, or with full background visual fields. Somatosensory information can be altered using unstable, uneven, or a small base of support during sitting, walking or standing positions. Difficulty of the training is increased gradually by adding vestibular stimulation such as incorporating head movements.[11-13]

2.4.2 Mechanisms of recovery from vestibular dysfunction

Understanding the mechanism of recovery is essential for successful vestibular rehabilitation. The brain has an important role to adapt the VOR with vestibular lesions and impairments of vestibular, visual, or somatosensory mismatch. Adaptation of the VOR starts when the vestibular system sends error signals and asymmetric levels of tonic activity that cause spontaneous nystagmus and gaze instability during head motion.[106] The CNS during adaptation detects the error signals and adjusts signals to decrease spontaneous nystagmus. The key feature in VOR adaptation is the role of vision during the habituation training. The long term visual error signals during head motion or visual vestibular mismatch adaptation strategies are important to enhance VOR adaptation. Another important factor for the adaptation program is the repetitive constant low frequency stimuli that contain vestibular error signals.[106]

Brain studies suggest significant changes in cortical and sub-cortical areas during habituation programs.[107] The role of vision in vestibular adaptation has been studied in both cortical and sub-cortical areas. During static vestibular imbalance, spontaneous nystagmus with the slow phase toward the affected side occurs without head movement; with static vestibular imbalance, vision can reduce the velocity and facilitate the suppression of the spontaneous nystagmus.[106] However, nystagmus velocity will be reduced with time even without the influence of vision after the restoration of the function of the affected ear.[106] Strategies like suppression of activity of the intact ear to balance both ears signals may occur at early stages.[108, 109] Suppression of signal activities from the intact ear for long period of time may increase the sensitivity of the intact ear as an adaptive response.[110] In the later stages, individuals may use compensatory strategies to compensate for reduced signals from one ear by using saccadic responses.[111, 112]

Vestibular symptoms aggravated mostly by head, body, or the surrounding motion is considered dynamic vestibular imbalance.[106] Visual information is critical for recovery from the dynamic vestibular imbalance. Vestibular ocular reflex gain does not improve without visual inputs.[106] For dynamic vestibular imbalance and during head movements, the slippage of images on the retina is sent from the occipital lobe to the caudal structures (the brainstem going through the nucleus of the optic tract to the inferior olive and the cerebellum and the vestibular commissure).[106]

Important phases of adaptation occur in the cerebellum and the vestibular commissure.[113] The compensation and the adaptation processes start from the inner ears where vestibular information (from the intact and from the residual of the impaired ears) are sent to the central nervous system to be readjusted.[114] The vestibular nucleus on both sides of the vestibular commissure plays an important role in changing the neural tone activities bilaterally.[113] Tone level may be adjusted by both the vestibular nuclei and some deep cerebellar nuclei.[115-117]

The adaptation process is accompanied by membrane changes of the vestibular nuclei and specific transmitters may relate to some specifications regarding the level of the frequency (high vs. low) and the direction of motion.[118, 119] Changes in the vestibular nuclei occurs when the impaired VOR causes inappropriate drift of images on the retina, then error signals are sent via the inferior olivary nucleus and climbing fibers to the Purkinje cells in the flocculus, whereas vestibular information is sent to the parallel fibers.[120-122] A long term depression of synaptic transmission occurs between both the parallel fibers and the Purkinje cells in the vestibule-cerebellum to make the appropriate changes in the VOR.[120-122]

The flocculus is not only the site for VOR adaptation but also VOR motor learning processes can happen as well through error correction signals in the floculus target neurons.[106] In the cerebellum, other adaptation strategies can occur such as central preprogramming of eye movements.[123]

The cerebral hemispheres play an important role in vestibular sensation; vestibular projections to the cerebral hemispheres carry important information related to the sense of spatial orientation and motion perception.[124] Visual-somatosensory-vestibular information important for distinguishing self motion vs. the surrounding motion, the perception of the position of the body in space and the head on body, the ability to maintain a sense of a stable world during locomotion, the detection of visual-somatosensory-vestibular conflict, and the resolution of any sensory conflict are all processed in the cerebral cortex.[106]

There is a wide spread anatomic connection to and from the vestibular system to the cerebral hemispheres. The vestibular nuclei project excitatory vestibular neurons to the lateral and inferior ventro-posterior lateral thalamic nucleus (VPL) to report head motion activities in darkness, whereas descending projection neurons that are mostly inhibitory project from the cerebral cortex to the vestibulo-cerebellum.[125-127] Projections from the vestibular to the cerebral cortex lead to both activation of certain areas of the brain and deactivation of activities in some areas of the brain.[106]

The cerebral cortex, particularly the Peri-Insular Vestibular Cortex (PIVC), receives information not only from the vestibular system but also visual and somatosensory stimuli, and vestibular neurons in the PIVC are activated not only by vestibular stimuli but also somatosensory and visual stimuli; sensory information conflict may cause feelings of nausea, motion discomfort and motion sickness.[128-131] The relationship between the visual and vestibular system in the cerebral cortex is a reciprocal interaction that is used for motion perception, spatial orientation and for resolving sensory conflict when one side of the brain views the world moving and the other side perceives the world not moving. The interaction between the two hemispheres plays an important role in solving sensory conflict among sensory channels by up-weighting some information and down-weighting other information.[106]

Mechanisms of habituation, adaptation, and sensory substitution can explain the success of vestibular rehabilitation for individuals with vestibular disorders. During habituation, graded exercises are used to train the brain and to decrease the response to the visual, vestibular, and somatosensory stimuli, and to facilitate desensitization of symptoms resulting from sensory conflict among visual, vestibular, and somatosensory systems. The central nervous system is trained to correctly up-weight and down-weight sensory inputs to improve postural control.[132] Short term compensation occurs after a lesion in the vestibular system and leads to reductions of symptoms like nausea, unsteadiness, and motion sensitivity. Chronic dizziness occurs when short term compensation is disrupted because of the severity of the lesion or impairment in the CNS.[1, 95, 133]

Vestibular rehabilitation provides long term improvements for vestibular disorders. Vestibular adaptation exercises to the VOR during the movement of the image on the retina combining head movement and visual inputs to the CNS can cause long term VOR adaptation.[134-139] Vestibular habituation to provoking stimuli also leads to long term improvement. The provoking stimuli of either visual or visual-vestibular conflict are repeated at regular intervals aiming to raise the threshold at which symptoms are aggravated. The general role for vestibular habituation to such stimuli is that stimuli are provided slowly and the increase in the stimuli should be according to the individual's tolerance.[140, 141]

The vestibular system is context specific plastic and the adaptation of the VOR depends on the frequency, direction, and environment of habituation.[142-147] The success of vestibular habituation depends on providing the appropriate error signal that drives vestibular adaptation. The error signal can be provided through visual stimulation such as optokinetic visual stimulation and visual flow signals to the CNS.[15, 82] Successful vestibular rehabilitation evaluates the sensory weighting for orientation in space and addresses performing exercises in altered visual/ somatosensory/ vestibular environments.[90, 148] The brain has the ability to weight and reweight the person's reliance on sensory modalities for orientation and postural control.[149] Virtual reality based therapy (VRBT) is one emerging technology that can be used in vestibular rehabilitation that may help individuals with vestibular disorders to lessen hypersensitivity to visual and motion stimuli, reduce the avoidance of activities, and progress self confidence.[15]

2.4.3 The use of virtual reality based therapy as a rehabilitation tool

2.4.4 Understanding the essential components of virtual reality based therapy (VRBT)

Webster's New Universal Unabridged Dictionary defines virtual reality based therapy as "an artificial environment which is experienced through sensory stimuli, sights, or proprioceptive inputs provided by a computer and in which one's actions partially determine what happens in the environment; also the technology used to create or access a virtual reality based therapy".[150]

Understanding the key components of VR explains the definition of VR. The key components of VR are the virtual world, the immersion, the sensory feedback, and the interaction.[151] The virtual world is an invented space displayed through a medium and can exist without being systemically displayed because it is much like a movie script and when viewed via a system in an immersive way called virtual reality based therapy. The second component of VR is the immersion into the environment. The state of immersion can be explained as the feeling of being in the invented environment either mentally, physically, or both; one can be mentally immersed when deeply and mentally involved.[151] One can be physically immersed when the body senses have the ability to be in the medium. For individuals with vestibular disorders, to be immersed in the VR, one has to be physically immersed, and the quality of the VR medium and software depends on its ability to be physically and mentally immersive to the participant. The third component of VR is the sensory feedback provided by the VR to the subject based on their actions and bodily movements. The participant receives immediate interactive feedback from the VR (mostly visual feedback) while being able to affect events and objects in the virtual world. The VR provides sensory feedback using many tracking systems including tracking systems to the head, hand, legs or any major body joints. The fourth component of VR is the ability of the virtual environment objects to interact with the user and the ability of the user to interact with the environment by being able to move within the environment, change positions of objects within the environment, picking them up or putting them down, to give the sense of being an effective and part of the environment.[151]

2.4.4.1 Interaction with VR: participant input to the virtual environment

The quality of the VR experience is greatly affected by the mechanism of monitoring the participant interactions during the VR experience.[152] The VR system has to be able to accept input from the participant to be sufficiently interactive, and the VR user has to be able to influence the VR system using appropriate input tracking systems. For the VR system to provide optimal physical immersion to the user, it has to accept active and passive forms of input from the user to provide monitoring to the participant interaction. Active ways of input monitoring include the response to the user commands either through joysticks, dashboards, keyboards or verbal commands. A key component to VR is the passive way of tracking body positions and movements in the space. Position tracking informs the VR system the location of the participant in space, and sensors tracking are usually used to track the head and or the hands in space. Immersion and quality of the experience is affected by the level of accuracy of the position tracking methods. Examples of tracking systems are described below:[152]

1. Locomotion based tracking: The Balance Near Automatic Virtual reality based therapy Device (BNAVE) is a custom-built treadmill with a maximum velocity of 1.2 m/s. At the front end of the treadmill is a grocery cart that is instrumented with two load cells on the push bar. The velocity of the treadmill and movement within the environment is controlled by the force and direction applied to the cart providing active input for user locomotion monitoring (Figure 2-2-1).[152]

Figure 2-2-1: Locomotion based tracking

2. Inertial tracking: including an accelerometer and inclinometer that provide passive input to the VR system user monitoring. Accelerometers detect the motion of the user by measuring the change in acceleration; inclinometers provide information about changes in inclination. Inertial tracking provide information about change in orientation in space.[152]

3. Body tracking: the use of tracking systems to provide either passive or active input from the user body as feed forward to the VR. Body tracking includes tracking of the position and movements of the head, eyes, hand, fingers, feet, or torso.[152] The load cells on the push bar in the BNAVE are one form of body tracking systems. The velocity of the treadmill and movement within the environment in the BNAVE is

controlled by the force and direction applied to the load cells on the cart providing active input for user locomotion monitoring.

4. Platforms: platforms provide passive and active input to the VR monitoring the user. Information coming from the platforms provides balance information to the VR system and also provides an interactive experience for the user. Platforms also provides the opportunity for controlling the difficulty of the interaction with the VR world.[152]

2.4.4.2 Interaction with VR: VR output to the participant

The output of the VR is the information presented to the body senses through sensory (visual, aural, or haptic) displays according to the available sources and the goal of the experiment. For all sensory displays there are three categories of VR output displays: head based, stationary based, and hand based. Displays related to the visual sense will be described. The general properties of visual displays and how that affects the quality of the experience including mental and physical immersion will be described.[153]

The quality of the VR experience is influenced by the visual images presented. The quality of the visual displays can better be measured through the following factors:[153]

1. The resolution of the visual display, which is affected by the size of the screen and the distance of the display from the eye, is a critical factor for the appropriate choice among the stationary, head based, and the hand based displays.[153]
2. Contrast and brightness of the visual display have a positive impact on the VR experience since a picture with good contrast makes it easy for the user to distinguish dark from light objects in the VR world; high brightness usually makes the VR

experience better. Both factors are influenced by the size and the distance from the eye are also critical in choosing the type of display.[153]

3. The user ability to move with freedom and have few constraints like space limitations, cables connected to the displays, and tracking systems. Each type of display allows for a specific range of mobility, consequently impacting the immersiveness of the VR experience.[153]
4. Portability of the visual display, safety, and the cost affect the choice among the three display categories.[153]

The BNAVE is a multi screen environment that displays the virtual world in 3 screens, 2.4 X 1.8 m (vertical X horizontal), surround the subject. The BNAVE has 16 aisles with 8 levels of visual complexity that depend on the spatial frequency and contrast of the product textures. The aisles increase in complexity from aisle one to aisle sixteen. The subject is approximately 2.9 m from the front screen. The images are displayed using Epson 810p PowerLite LCD monoscopic projectors, with a pixel resolution of 1024 X 768 for each screen. The update rate of the images is consistently at least 30 frames per second.

The different paradigms used for visual displays including stationary displays the projection based VR, and head based VR will be discussed.[153]

Projection based display

The projection based display VR has a large screen and usually surrounds the user in a cave like environment giving the user a larger field of VR view. The projection based displays a less real world view and a large area to move which all enhance immersion.[153] The cave like projection based displays require big screens, back projecting projectors, body tracking systems that may cover the hands and the movement inside the VR cave, and multiple computers synchronized together to control the cave VR system. The projection of the VR onto large screens requires high resolution and high cost. The user in the cave projection VR is not isolated completely from the real world. The user stands away from the screens which decreases the eye strain developed during standing in front of screens and allows the user to remain for longer times immersed in the VR experience. Advantages of projected displays include 1) they provide a large field of view; 2) less eye strain and longer immersion time in the experience; 3) higher resolution; 4) fewer cables connected to the user; and 5) better mobility.[153]

Head mounted display

The HMD presents the virtual world to the user through lenses, but provides less immersion compared to the projection based display. Another advantage of head based displays is that the HMD only requires small light screens that allow the user the ability to move more freely in more open areas since screens move with the user's head. The selection of head based displays can provide wide selection of tracking systems. However the user is more subject to eye strain resulting from the near screens, which limit the time of the experience. Neck strain may also be associated with heavy head mounted displays. Advantages of head mounted displays include 1) the HMD field isolates the user from the real world; 2) lower costs and may be easier to build than cave like environments; and 3) less concern about surrounding environmental factors such as lighting and space. A disadvantage of the HMD compared to a projection based display is that it provides a limited field of view.[153]

2.4.4.3 Interacting with VR: ways of interaction

The ability to interact with the virtual world between oneself and the VR is what differentiates VR from other systems, which provides the sense of presence and immersion. Interaction with the VR occurs through many means including manipulation and navigation.[154]

Manipulation is the ability of the user to adjust, change or transform the virtual world objects through selection of virtual items by the user. Selecting an object in VR occurs through indicating the direction or picking an item. Operating an action usually occurs through positioning, locating, arranging, and sizing the objects. Manipulation can occur through physical control where the user is able to apply force to real devices like buttons and switches. Manipulation can also occur through direct control where the user acts in the VR world as they would in the real world by performing body movements required to accomplish a task.[154]

Navigation occurs when the user moves in the VR world from one place to another walking or driving. In the BNAVE (the grocery store model), the user has the ability to navigate in the store using a physical manipulation method (the load cells in the push par) to walk and navigate through the virtual world.[154]

2.4.4.4 Immersion in VR

Both physical and mental immersions are important elements of the VR experience and are affected by the design of the virtual world and the goal of the experiment. Physical immersion is the critical unique factor that distinguishes VR from other media and systems. To have physical immersion in the virtual world, the set up is affected by the location and orientation of the user inside the virtual world. The virtual reality based therapy device provides stimuli to the user about their location and actions in the environment as the system tracks actions of the user and sends responding images, sounds and tactile information to the user. The presence of physical immersion means the experience is VR and the absence of it means it is not VR.[155]

The second form of immersion is mental immersion; the presence and importance of being mentally immersed depends on the goals of the experience in which some experiments consider it critical and desirable. Physical immersion is important for the experience to make it VR, and it also affects the level of mental immersion. The level of physical immersion affects the level of realism which also influences mental immersion. The level of sensory immersion required to establishing mental immersion is still not known. There are other factors affecting mental immersion other than physical immersion. Resolution of the displays, the quantity of sensory tracking systems and how many senses are engaged in the experience, plus the amount of time between action tracking and system response are important factors affecting the level of immersion.[155] The level of immersion may differ for different projection based systems. Projection based systems like the BNAVE may provide better resolution than the head projection-based and sufficient physical and mental immersion.

2.4.5 Rationale: The use of VRBT in vestibular rehabilitation

Virtual reality based therapy has been used as a rehabilitation tool for individuals with neurological impairments after stroke, and showed to be a promising tool for community ambulation, gait training, sensorimotor training and hand function training (Table 1). Virtual reality based therapy (VRBT) is one emerging technology that can be used in vestibular rehabilitation. Virtual reality based therapy provides the possibility for precise control in treatment environments within which individuals can be exposed to a range of stimuli that are difficult to be controlled for in the real world. In VRBT, an artificial environment that simulates the real world is created for the individuals to provide more personalized and controlled intervention programs.[156]

Table 1: The use of virtual reality based therapy in the rehabilitation of persons post stroke

Intervention	Virtual reality based therapy Software	Evidence for improvement	Outcome measures
Sensorimotor training	-VR PlayStation-2 with eye toy	Flynn, S. et al 2007.[157]	**1.** Dynamic Gait Index **2.** Fugl-Meyer Assessment **3.** Berg Balance Scale
Community ambulation and gait rehabilitation	-Virtual reality based therapy based treadmill -Robot VR	Yang Y. et al 2008,[158] and Fung J. et al 2006.[159] Mirelman, A. 2009.[160]	**1.** Gait speed **2.** Walking time **3.** Walking ability questionnaire **4.** Activities Specific-confidence scale
Attention and compensation training	-Crossing street training Desktop model	Kim, J.et al 2007.[161]	**1.** Attention through responding to visual stimuli **2.** Successful rate of number of crossings

Individuals with vestibular disorders report increased symptoms in visually complex environments and demonstrate increased sway when exposed to full-field visual motion, possibly because they become more dependent on information from non-vestibular systems, particularly vision.[3, 6] Subjects with inner ear disorders have more sway when asked to close their eyes with or without sway reference disturbance; the incidence of falls increased when the subjects are asked to close their eyes while standing.[3, 6] The importance of visual information increases when both somatosensory and vestibular systems are impaired.[105]

Virtual reality based therapy may be an ideal way to provide habituation exercises for individuals with vestibular disorders who become symptomatic in complex visual environments. During treatment of individuals with vestibular disorders, part of the intervention for postural control disorders is to practice visual-vestibular and/or somatosensory-vestibular alterations.[11-13] Manipulation of sensory information should start gradually with one sensory modality, then multiple sensory alterations are advised. Visual information can be altered in the intervention by asking subjects to move their head side to side or in the vertical plane; subjects may be asked to perform exercises in visually busy environment, in poorly lit environment, or with full background visual fields. Somatosensory information can be altered using unstable, uneven, or a small base of support during sitting, walking or standing positions. Difficulty of the training is increased gradually by adding vestibular stimulation such as incorporating head movements.[11-13]

Some individuals with vestibular disorders report an increase of symptoms in visually complex environments such as busy places, grocery stores, and environment with flickering and fluorescent lighting plus crowds.[162] Several groups have used provocative visual stimulation to adapt the VOR to habituate dizziness in people with vestibular disorders. Viirre (2003) reported an experience of postural instability and vertigo after one exposure to virtual reality based therapy display with a subject with no history of inner ear problems.[163] He also used visual displays as an incremental adaptation protocol in another experiment with subjects with low VOR gain and found that VOR gain increased significantly after the experience compared to the control group with head movement exercises without the visual display.[14] Pavlou (2004) reported significant improvement in posturography scores and visual vertigo symptoms in individuals with vestibular disorders after the use of desensitization exposure to optokinetic visual stimulation with whole body or surround rotation as a habituation tool.[15] The Wii Fit is one application of virtual reality based therapy that has been used for rehabilitation of individuals with neurological disorders and balance problems.[164] Nitz (2010) used the Wii Fit form of virtual reality based therapy to improve balance and increase strength among ten young (30-58 years) healthy women. The intervention program included a one hour practice on the Wii Fit for ten weeks. Subjects' balance and strength improved significantly after the ten weeks on measures including the modified clinical test for sensory integration, the step test, and the Timed Up and Go. The Wii Fit virtual reality based therapy is used in combination with a physical activity program to treat two young individuals with poor walking ability and week interaction abilities with people affecting performance of activities of daily living. The intervention program helped the two people to significantly increase their level of physical activity and walking from one destination to another.[165]

Virtual reality based therapy using the BNAVE (grocery store version) may be an ideal method for visual habituation training for individuals with vestibular disorders since the healthcare provider can control the amount and intensity of the visual stimuli according to the individual situation and progress. The VRBT may help individuals with vestibular disorders to lessen hypersensitivity to visual and motion stimuli, reduce the avoidance of certain activities, and progress their self confidence. Habituation exercises are one method to decrease space and motion sensitivity and to decrease the dependence on one type of sensory feedback for postural control. The vestibular rehabilitation goals are to (1) enhance perception of orientation and motion in busy environments, (2) use various sensory strategies for balance, (3) improve gaze stabilization, (4) VOR adaptation, (5) sensory substitution, and (6) reduce functional disability and improve quality of life.

2.5 BALANCE ASSESSMENT FOR PERSONS WITH/WITHOUT VESTIBULAR DISORDERS: POSTUROGRAPHY

Postural control can be described as the ability to control body position in space in different environments that require different tasks. Postural control involves the maintenance of the alignment of the body posture and a vertical relationship against gravity forces. Maintenance of equilibrium, the projection of the center of gravity of the body inside base of support boundaries, is another function of postural control. The relationship between the body segments in respect to each other and between the body segments in respect to the surrounding environment can best describe postural orientation. The central nervous system must have an accurate picture of the body orientation in space, while sensory information from vision, somatosensory and vestibular systems monitor the body interaction in space.[166, 167]

Postural control is essential in every task performed, postural control is important in activities like sitting, standing, walking, and running performed in different environments. For every task requires postural control, postural control has stability component and orientation component that change with every task and environment.[167, 168] Postural orientation during sitting includes orientation of head position, gaze position, and hand position, while size of base of support during sitting influences the stability component of postural control. During standing, position of head and gaze influence the orientation component of postural control. The stability component during standing requires controlling center of total body mass (COM) and center of gravity (COG), the vertical projection of the COM, relative to the stability of the base of support (unstable base of support include standing in a bus, foam, or challenging surfaces).[169] Orientation and stability are influenced by neural components such as: sensory/perceptual processes (organizing sensory information from somatosensory, vision, and vestibular systems for balance), motor processes (organizing motor synergies for balance), and cognitive processes (organizing adaptive anticipatory sensory and motor strategies to changing tasks and environmental changes).[169]

2.5.1 Measures of postural control

Understanding the functions of balance variables is important in understanding postural control. Center of mass (COM), center of gravity (COG), center of pressure (COP), base of support (BOS), and limits of stability (LOS) all have been used to measure and define balance. Center of mass is a passive variable that represents the center of total body mass controlled by the balance systems; the vertical projection of COM onto the ground is called the COG.[169, 170] The common balance variable that has been used in many studies of balance is the position and velocity of COP. Center of pressure represents the center of distribution of the total force of body weight on the ground.[171] Center of pressure is an active variable that moves continuously in all directions and has been recorded in anteroposterior (A/P) and mediolateral (M/L) directions. The COP moves around the COM to keep the COG within the base of support. The area of the body in contact with the ground is called the BOS, while the boundaries within which the body can maintain balance without losing balance or changing the base of support is called the LOS.[170, 172] Because LOS is not fixed and changes with different tasks and environments due to varied body reactions, strength, and joints flexibility, it has not frequently reported in many balance research studies.[173]

Quiet stance is associated with small amounts of sway that help the body to maintain equilibrium, the backward and forward sway during standing provide feedback information to the nervous system about postural orientation and help the body to maintain equilibrium.[18] During quiet stance, body sway in the (A/P) direction is controlled by the relationship between COP and the vertical reaction force; the optimal relationship between the two factors with less body sway would be equal and opposite in direction. During forward sway, body weight force would be greater than the vertical reaction force making the body experience a clockwise angular acceleration, COP will increase and will be anterior to the COG. Muscles around the ankle (planter-flexors and dorsi-flexors) are continuously active to regulate the relationship between the COG and the COP, and COP is always moving in all directions somewhat greater than the COG and around the COG.[174, 175]

Ankle muscles have a major role during ankle strategy for balance control. The ankle strategy involves the activation of ankle evertors (peroneii), invertors (tibialis anterior and posterior, extensor digitorum longus, and hallucis longus), planter-flexors, and dorsi-flexors. The A/P control of balance requires collaborations between the right and left planter-flexors and dorsi-flexors that control the COP in the anterior/posterior direction. The M/L control of balance requires the collaborations between the right and left evertors and invertors plus hip muscles that control the COP in the medial/lateral direction.[173, 176, 177] Center of pressure path length in both A/P and M/L directions was studied, center of pressure change was higher in A/P directions than in M/L direction; during quiet stance the hip provides the load/unload mechanism that makes the changes in M/L COP limited whereas the A/P control of COP occurs at the ankle level during ankle strategy.[178-181]

2.5.2 Postural control strategies during quiet stance

2.5.2.1 CNS contribution to postural control

The CNS has an important role in controlling postural orientation and stability during task/ environment changing demands. The cerebellum controls postural adaptation and muscles response magnitude due to task/environment requirements. Brainstem nuclei role in postural control include: 1) regulation of muscles facilitation/inhibition activities and muscle/postural tone adjustment for postural control, and 2) regulation of sensory information important for anticipatory movements strategies for balance control. Spinal cord neural circuitry controls postural tone and activates antigravity muscles.[182-184]

The CNS must organize sensory information form visual, somatosensory, and vestibular systems to have an accurate picture of postural orientation and to know when and how to generate appropriate movement strategies for controlling balance in space.[16, 17] Sensory information from vision provides important information to the CNS concerning the position and motion of the body relative to the environment. Vision provides a reference for the relationship between the body and the surrounding as a reference for the verticality of the surroundings and a reference for the relative motion of the body in space. Visual information is not the only type of information important for postural control.[19] Center of pressure sway magnitude may differ when exposed to accurate vs. inaccurate visual information. Information to the CNS about body position and movement in space relative to the support surface is provided by the somatosensory system. Center of pressure sway magnitude may differ when standing in different support surfaces that provide accurate vs. inaccurate somatosensory information. Information to the CNS about movement and acceleration of the head in space is provided by the vestibular system. Center of pressure sway magnitude may differ among persons with or without intact vestibular information.[20]

2.5.2.2 Sensory organization and motor strategies during quiet stance

Sensory organization for postural control has been discussed by many theories to describe how the CNS integrates sensory information for balance across changing environments. An old theory, intermodal theory of sensory organization, discuss that all three senses (vision, somatosensory, and vestibular) are used equally for orientation, and these systems provide information that act independently from each other but they all contribute to increasing postural control specificity.[185] The intermodal theory excludes the idea of sensory conflict among sensory systems and considers that the relationship among sensory information in the CNS to be invariant relationship.[185] The new theory, the sensory weighting model, suggests the three senses for balance and orientation do not act independently, and does not agree with the idea that all the three senses act equally for orientation. The theory suggests that the three senses not only contribute to increasing postural control specificity; but depending on task/environment difficulty, in some conditions inaccuracy for orientation may happen from any of the three senses. The theory suggests that the CNS takes into account the task/environment characteristics for orientation and postural control, and modifies the weight and importance of sensory input and resolves sensory conflict that may happen in altered sensory environments, to enhance stance in different sensory conditions.[186-190] In conditions where visual information becomes inaccurate for orientation and postural control, the CNS will decrease reliance on vision, and increase reliance on somatosensory information. Lee et al. studied the sensory weighting model and discussed sensory weighting on vision for postural control during leaning a new task in a different environment. A person will increase reliance on vision in the early phases of a new task/environment, and will decrease reliance on vision as the task/environment becomes automatic.[191] In environments where somatosensory is inaccurate or less reliable, reliance on vision increases while reliance on somatosensory decrease.[186-189, 192]

Nashner et al. studied sensory organization and body sway in six different conditions that investigated the effect of presence/absence and accurate/inaccurate sensory information from vision and somatosensory systems. Condition 1 examines how the 3 systems (vision, vestibular, and somatosensory) contribute to balance control. Condition 2 and 3 examine how absent or inaccurate visual feedback information may influence balance control. Condition 4 examines how inaccurate somatosensory information influences balance control. Conditions 5 and 6 examine how inaccurate somatosensory plus the absence or inaccuracy of visual feedback may influence balance control.[189, 192]

The role of sensory systems for postural control has been studied in the 6 sensory organization conditions. Amplitude of COP sway in condition 2 in healthy individuals increased compared with COP sway with eyes open, suggesting that visual information is an important but not required factor for postural control.[191, 193, 194] Center of pressure sway amplitude and velocity also increased when vision provided inaccurate information for balance (condition 3), suggesting that not only presence of vision is an important factor for balance but also accurate visual reference that matches information from other sensory systems are important for balance control.[191] Center of pressure sway also increased in healthy individuals when exposed to platform perturbations (condition 4) compared with (condition 1).[195-197] Individuals with vestibular disorders may lose balance or fall in conditions that force them to use vestibular information only for balance such as condition 5 and 6.[198]

Measuring sensory control during standing has been investigated using subjective and objective measures of sway. Shumway-Cook and Horak (1986) described a subjective method for measuring sensory control during standing. The method uses a dome and foam to provide inaccurate somatosensory and visual sway referenced feedback. The foam provide destabilization in conditions 4, 5, and 6; the dome provides visual vestibular conflict in conditions 3 and 6. The therapist observes the subjects sway and subjectively quantifies the amount of sway on a scale 1 to 4 (1= minimal sway, 2= mild sway, 3= moderate sway, 4= fall).[199]

Objective ways of quantifying sway have been developed using computerized dynamic posturography (Equitest™). The Sensory Organization Test (SOT) of the Equitest is used to measure sensory control during standing. The SOT uses a tilting floor and moving walls to provide inaccurate somatosensory and visual sway referenced feedback during standing. Tilting of the floor only provides sensory destabilization in the antero-posertior (AP) direction; the movement of the walls is also in one direction (AP) . The SOT quantifies sway objectively by calculating an equilibrium score, an initial dynamic alignment score, and a strategy score. The equilibrium score indicates how well the subjects remains within the limit sof stability during each SOT condition; the equilibrium score is calculated using the following formula:

$$\text{Equilibrium} = \frac{12.5\,° - (\theta\max - \theta\min)}{12.5°} \times 100$$

The normal limits of stability is 12.5° of AP sway. Equilibrium scores range between 0 – 100, 0 indicates that the subject is reaching the limit of stability due to high sway, and scores near 100 indicates that the subjects' sway is very small. In cases where a subject falls, no equilibrium score is recorded. The initial alignment score reflects the average position of the subject COG 700 msec before each trial. The dynamic alignment score reflects the average position of the subjects' COG during the 20 second trial. The strategy score indicates the strategy used during the 20 second trial and it is calculated using the following formula:

$$\text{Movement strategy} = \left[1 - \frac{(SHmax - SHmin)}{25}\right] \times 100$$

The difference measured between the highest shear force and the smallest shear force is 25 pounds. Movement strategy scores range between 0 – 100; scores near 100 indicates that the subject used an ankle strategy, and scores near 0 indicate that the subject used a hip strategy during the trial.[200]

The difference between using the foam vs. tilting floor that provide inaccurate somatosensory sway referenced feedback has been studied to investigate balance deficits. Allum et al (2002) compared the amount of sway associated with standing on a foam eyes open/ closed, standing on a tilting floor with pitch ankle sway referencing eyes open/ eyes closed, and standing on the tilting floor with lateral ankle sway referencing eyes open/ eyes closed (using Neurocom Equitest SOT conditions 4 and 5). Sensors were mounted on a belt to quantify sway on the foam. The foam provided multidirectional sway across all frequencies in the range 0.8- 5.2 Hz. Standing on the tilting floor with sway in the pitch direction only increased body sway in the pitch direction with different characteristics to sway in the AP direction than on the foam. Sway in the lateral direction only increased body sway in the lateral direction with similar characteristics to sway in the ML direction on the foam. The foam showed to be easier to use and provide more difficult balance task for subjects.[201]

2.5.2.3 Psychometric properties of the Computerized Dynamic Posturography: SOT protocol

The functional contribution of vestibular, visual, and somatosensory inputs for postural control and balance is measured using Computerized Dynamic Posturography (CDP). The psychometric properties of CDP protocols including clinical efficacy, cost effectiveness, validity, and reliability have been established.[202] The CDP protocols include the SOT test that assesses balance, and tests the subject's abilities to use, select, and organize sensory inputs from vision, vestibular system, and proprioceptive system under sensory conflict conditions. The clinical efficacy and cost effectiveness of SOT have been established in the literature.

The validity of SOT protocol has been tested among individuals with vestibular disorders. El-kashlan et al. evaluated the clinical validity of balance measures including the SOT in the management of individuals with vestibular disorders, and found that the SOT is an important test for individuals with vestibular disorders.[203] The SOT showed to be a sensitive test to diagnose individuals with dizziness.[204] The SOT also showed to be able to distinguish between individuals with bilateral vestibular loss and normal subjects, and to identify individuals appropriate for vestibular rehabilitation.[205, 206]

The efficacy of SOT in measuring health outcomes for individuals with vestibular disorders after a vestibular rehabilitation programs has been investigated. Perez et al. treated individuals with chronic peripheral vestibular disorders and used SOT to measure its impact on health outcomes. The SOT provided significant information related to individuals improvement after vestibular rehabilitation.[207] SOT results were used to customize vestibular rehabilitation programs for individuals with peripheral vestibular loss. Individuals received customized vestibular rehabilitation based on SOT results showed significant improvement.[208]

Test retest reliability of the SOT has been established. Test-retest reliability of SOT among young healthy subjects (< 50 years), conditions 4-6, were fair to good reliability, range (0.35-0.79).[209] The SOT test-retest reliability, conditions 3-6, among elderly healthy individuals was measured; reliability was moderate to high, range (0.73-0.94).[210]

2.5.3 Aging and postural control

Aging is an important factor that influences postural control. A decline in function of multisensory inputs and motor systems is associated with aging.[21, 22] The effect of age on postural control has been described in many theories that suggest that abnormal postural control may happen due to internal causes of aging genetically determined, external causes of abnormal postural control associated with aging related to environmental and nutritional factors, or the combination of both internal causes of aging and the external causes of abnormal postural control.[25] Studies of aging classifications consider individuals 60 years old and over as elderly adults.[211] Studies of gait and walking ability among elderly, healthy individuals over the age of 60, found great variability of sway among elderly individuals which can be explained by the theories of aging.[212]

Falls rates among elderly people are at least 33% per year, and considered the seventh most cause of death in people over 60 years.[23, 24] Fall as an indicator of instability is defined as the movements of the center of mass outside the limits of the base of support in which the person loses control and falls to the ground.[25] The American and British Geriatric Society and American Academy of Orthopedic surgery guidelines for prevention falls in elderly described 11 risk factors for falls including: visual problems, vestibular problems, use of assistive devices, muscle weakness, history of falls, balance deficits, gait impairments, cognitive deficits, arthritis, impaired ADLs, and age > 80 years.[25, 213]

2.5.3.1 Rationale: studying age effect on balance

With aging, there are changes in: muscle strength, endurance, and range of motion that may influence balance control. Muscle strength has been shown to decline as age increases. Anniansson et al.[214] compared muscle strength changes among healthy groups between 30 and 80 years, noted that forces production in the lower extremities declined up to 40 % with aging. Hughes et al.[215] investigated the impact of aging non-uniformity changes in muscle strength in a 10 year prospective study of individuals 60 years old. Lower extremities strength was reduced by 12 % to 17 % with aging. Muscle endurance declines with age, mostly lower extremities. Anderson et al.[216], Spirduso et al.[217], and Medina et al.[218] reported an age related change in muscles including: muscle size (become smaller), muscle tissues (exchange with fat), muscle fibers (lose fibers important for postural control (type 1) and muscle fibers important for running (type 2)), and neuromuscular junctions and motor units (lose motor units). Range of motion has been shown to decrease in all body joints with aging; arthritis is one common risk factor associated with aging that deteriorate range of motion. Lewis et al.[219] , Einkauf et al.[220] , and Studenski et al.[221] studied the age effect on spinal flexibility among young (20-29) healthy and old (70-84) healthy, spinal extension was reduced 50% in the elderly group compared with the young group.

Changes in sensory systems including: somatosensory system, visual system, and vestibular system are associated with aging. Vibratory sensation, tactile sensation, plus pressure sensation has been shown to be impaired with aging, especially in the lower extremities.[222-224]

Elderly individuals are more likely to be dependent on sensory information from vision and vestibular systems and more likely to have peripheral neuropathy in the lower extremities.[25]

Visual information including information about visual field, visual acuity, and visual contrast show to decline among the elderly groups.[225, 226] Changes in visual abilities in the elderly are associated with changes in the eyes sensitivity to the light.[225, 226] In conditions where visual information was inaccurate for orientation in space, COP showed more sway among the elderly healthy group compared with young healthy group.[227, 228]

Vestibular information to the CNS can be reduced with aging. Studies show that reduction of vestibular function with aging is associated with changes in the structure of the vestibular system. Rosenhall et al. reported that the vestibular system loses around 40% of the nerve and hair cells with > 60 years.[229] Reduction in the structure and function of the vestibular system among elderly people may increase COP sway, increase imbalance, and increase the probability of sensory conflict.[25]

2.5.4 Abnormal postural control: individuals with vestibular disorders

Falling is a risk factor associated with vestibular disorders that can impact quality of life (QoL) of individuals with vestibular disorders and reduce participation in daily life activities including physical and psychological aspects.[29, 31] Among 546 incidents of falling that resulted in a visit to an emergency department, 80% had vestibular impairments and 40% were complaining of vertigo.[10] The incidence of falls among individuals with bilateral vestibular loss (51%) is significantly higher than the incidence of falls in the general population (25%) in people between 30-80 years of age.[29]

Vestibular disorders may influence alignment, muscular coordination and postural synergies.[230] Abnormal alignment, restricted joint movements, and abnormal COM/COP sway magnitude are associated with vestibular disorders.[230] Abnormalities of body alignment and joints range of motion can be interpreted as musculoskeletal impairments or as compensatory strategies for balance control.[231]

Horak at al.[232] used Sensory Organization test to measure the magnitude of COP sway among individuals with vestibular disorders. Interrupting sensory information from the legs among healthy individuals increased COP sway. Intact vestibular information assists subjects to maintain balance when somatosensory or visual information are disrupted. Individuals with vestibular disorders when tested during conditions 5 and 6, where information from both vision and somatosensory is reduced or made inaccurate, COP sway increased and subjects experienced sudden falls.[232]

2.5.4.1 Rationale: studying vestibular disorders effect on balance

Measuring postural control may help to differentiate between individuals with sensory conflict/over reliance and/or sensory selection problems for balance control. Subjects who are more likely to have inter-sensory conflict are more likely to have limited ability to organize sensory information.[25] Subjects with sensory organization problems are more likely to show an over reliance on visual information for balance if they are visually dependent for postural orientation. Their COP sway increases in situations in which visual information is absent or inaccurate.[233] Subjects who are over dependent on somatosensory information for postural orientation are more likely to experience increased COP sway in situations when sensory information from the lower limbs is absent or disturbed.[234]

Subjects who have sensory selection problems are more likely to have balance problems in any condition or environment with inaccurate of absent sensory information. Not every subject with balance problems can be categorized as over-dependent on sensory information or as experiencing sensory conflict because of limited sensory organization abilities. Subjects may have difficulties selecting the appropriate sensory information for balance when exposed to any environment with inaccurate or absent sensory information for balance.[235, 236]

Examining balance in the 6 conditions of the sensory organization test (SOT) provides insights into the persons' ability to organize and select sensory information appropriate for balance which may demonstrate the type of environments and tasks responsible for imbalance.[25] In situations where a subject falls or COP sway increases with disruptions of somatosensory information from the lower limbs, (condition 4, 5, and 6), subjects may be considered surface dependent.[237] During conditions where there is inaccurate or no visual information (conditions 2, 3, and 6), subjects may be categorized as visually dependent.[237] During conditions which involve disruptions of information from both visual and somatosensory systems (condition 5 and 6), a subject is more likely to experience increased COP sway leading to a fall if there are problems in the vestibular system. In situations when a subject experiences a large magnitude of COP sway in situation involving disruptions of visual or somatosnesory information (conditions 3, 4, 5, and 6), the subject may have sensory selection problem and may have an inability to correctly select sensory information for postural orientation.[238]

Sensory Organization test is the standard objective measure for balance. However, Sensory Organization test is expensive. The Balance Rehabilitation Unit is a new objective measure for balance that uses head mounted display device as part of the balance assessment and can measure balance in the same conditions used with Sensory Organization test. The Balance

Rehabilitation Unit requires less space and is considered cheaper in price, less than half the CDP price. The balance assessment module in the Balance Rehabilitation Unit might be used as an objective balance assessment modality for people with/without vestibular disorders. The psychometric properties of a new objective balance measure are important to be established in order for the device to be useful. The reliability and validity are the main psychometric properties to be examined. The Balance Rehabilitation Unit device needs to be compared to the CDP in healthy and individuals with vestibular and balance disorders. Table 2 summarizes the differences between the BRU and CDP.

Table 2: Differences between the Balance Rehabilitation Unit and Sensory Organization test

Stimulus	Sensory Organization test	Balance Rehabilitation Unit
Visual stimuli: condition 3 and 6	Walls around the subject move in the A/P direction with the body sway. Walls do not move in the M/L direction of the body sway.	Goggles present a virtual basket ball court. Visual scene, HMD, moves with the body sway in the A/P direction, and M/L direction. Visual scenes presented via HMD may provide better visual reference than walls.
Somatosensory stimuli: condition 4, 5, and 6	The floor moves with the body sway only in one direction A/P direction. The destabilization does not cover M/L direction.	Subject stands on a foam that provides destabilization in A/P, M/L.
Space	Large space required	Small space required
Price	Expensive	Less expensive

2.6 SPECIFIC AIMS

2.6.1 The use of virtual reality based therapy as an intervention tool

Aim 1: To examine the use of virtual reality based therapy as an intervention for individuals with vestibular disorders. The study will examine the effect of a VRBT intervention on self report measures and performance measures to determine the immediate and long term (6 months) effect of VRBT on gait, balance, nausea, headache, dizziness and visual blurring symptoms.

Aim 2: To determine the difference of self report and performance measures between conventional therapy and the Virtual reality based therapy (VRBT) in persons with vestibular disorders.

Outcome measures include the Activities-specific Balance Confidence scale (ABC), the Dizziness Handicap Inventory (DHI), the Situational Characteristics Questionnaire (SCQ) part A and part B, the Visual Analog Scale (dizziness, headache, visual blurring, nausea), and the Simulator Sickness Questionnaire (SSQ). Performance measures include the Functional Gait Assessment (FGA), the Dynamic Gait Index (DGI), gait speed, the Timed Up and Go (TUG), and the Sensory Organization Test (SOT).

2.6.1.1 Research Hypotheses

Hypothesis aim 1:

Ho: VRBT will have no effect on self report and performance measures immediately after the intervention, or after 6 months of follow up, (no effect on gait, balance, symptoms of nausea, headache, dizziness, or visual vertigo) on individuals with vestibular disorders.

Hypothesis aim 2:

Ho: There will be no difference on self report and performance measures between conventional therapy and the Virtual reality based therapy (VRBT) in persons with vestibular disorders.

2.6.2 The use of Balance Rehabilitation Unit for balance assessment

The purpose of this study is to examine the reliability (test retest) and convergent validity of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders compared with a standard objective measure of balance, the Sensory Organization test.

2.6.2.1 Specific aims

Aim 3: To examine the test-retest reliability of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders by examining balance twice in every subject.

Aim 4: To examine the convergent validity of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders by comparing the results of the Balance Rehabilitation Unit with the results of the Sensory Organization test.

Aim 5: To examine group differences among the study groups (young healthy vs. old healthy vs. individuals with vestibular disorders) in the BRU and CDP six balance conditions.

2.6.2.2 Research hypotheses

Hypothesis aim 4:

Ho: There is no correlation between the two devices.

Hypotheses aim 5:

Ho: There will be no significant differences in the amount of sway in the BRU sensory conditions among study groups.

Ho: The amount of sway in the young healthy subjects will be similar to the amount of sway for the older healthy group and young individuals with vestibular disorders.

Ho: There will be significant difference in the amount of sway between the older healthy group and individuals with vestibular disorders.

3.0 METHOD

3.1 THE USE OF VIRTUAL REALITY BASED THERAPY IN VESTIBULAR REHABILITATION

3.1.1 Study design

The study was a clinical trial designed to compare 2 interventions in a group of individuals with vestibular disorders across 3 time points (pre, post, and 6 month follow up). The first group of 20 subjects was treated with conventional vestibular rehabilitation. Subjects were treated for 6 treatment sessions (one session per week) by a physical therapist. The intervention included gaze stabilization exercises, functional gait and balance exercises. The second group of 20 subjects was treated using a virtual reality based therapy cave-like environment (the grocery store VRBT). During the treatment session, subjects received habituation training during ambulation in the grocery store. Subjects turned their head right and left while looking for grocery products while walking. Each subject was treated for 6 treatment sessions in the VRBT for 6 weeks. Each treatment session consisted of 6 (4 minute) trials for a total of 24 min/session.

3.1.2 Inclusion criteria

The study consisted of 40 subjects who had peripheral, central, or mixed vestibular disorders. Subjects were recruited from the vestibular disorders clinic after examination by a neurologist. The protocol was approved by the Institutional Review Board. All subjects were provided informed consent and agreed to participate in the study. The benefits and risks of the study were explained to participants during the recruitment period.

3.1.3 Intervention

3.1.3.1 Virtual reality based therapy (VRBT)

The virtual environment consisted of a grocery store modeled in 3D Studio Max and imported into Unreal Tournament (UT2004), adapted for multi-screen environments with the CaveUT modification. The store was displayed on 3 screens that surrounded the subject in a full-field CAVE-like environment. The store contained 16 aisles (20 m long) and had 8 levels of visual complexity that depended on the spatial frequency and contrast of the product textures. The aisles increased in complexity from aisle one to aisle sixteen.

Three 2.4 X 1.8 m (vertical X horizontal) back-projected screens were arranged as shown in figure (2.2.1). The side screens make an included angle of 110º with the front screen. The front screen is 1.5 m from the user, and the opening of the structure at the location of the subject is approximately 2.9 m from the front screen. The images are displayed using Epson 810p PowerLite LCD monoscopic projectors, with a pixel resolution of 1024 X 768 for each screen. Each projector is connected to an NVIDIA GeForce4 graphics processing unit (64 MB texture memory) installed in a separate PC (Pentium, 2.2 GHz, 512 MB RAM) running Windows XP.

The movement of the images on the three PCs is synchronized and controlled by a server via a local area network. The update rate of the images is consistently at least 30 frames per second. The virtual environment is interfaced to a custom-built treadmill with a maximum velocity of 1.2 m/s. At the front end of the treadmill is a grocery cart that is instrumented with two load cells on the push bar. The velocity of the treadmill and movement within the environment is controlled by the force applied to the cart.

3.1.3.2 Conventional therapy

The aims and strategies of physical therapy interventions were focused to improve the symptoms and reduce the impairments. Examples of exercises and reasons for their uses were provided below:

- Symptoms of visual blurring and gaze instability in activities that require head movements such as shopping or walking in busy places: the aim of the treatment was to increase gaze stability during activities of daily living. Vestibular Ocular Reflex (X1): the individual views a stationary object while turning the head side to side until the point oscillopsia is induced; (X2): the target moves in the opposite direction of the head movement. VOR exercises can cause retinal slip error signals to drive the central nervous system (CNS) to enhance VOR gain that improves gaze stability.[239]
- Symptoms of space and motion sensitivity manifested as dizziness, nausea, and headache provoked in busy environments: the aim of the intervention was to teach the individual to control their symptoms to become less sensitive and more tolerant to such environments in their ADLs. Habituation training using gradually incremental tasks and contexts was used to decrease symptoms and improve space and motion tolerance. Individuals may start sitting in a busy environment, then walking without

head movement, walking in less busy places before more busy places, and walking with the flow of the crowd before walking against a moving crowd.[11, 12]

- Symptoms of dizziness increased by certain head movements: the aim of the treatment was to reduce symptoms with head movements. Habituation training was also used for this aim where the individual performed repetitive self exposure to exercises that aggravate symptoms. Symptoms of dizziness and vertigo may reduce temporarily in the early stages of the habituation training due to the reduction in the amplitude of excitatory postsynaptic potentials in the interneuron and motor neuron.[11, 12] To have a permanent reduction of symptoms, structural changes in the interneuron and the motor neuron, this needs to continue for weeks in order for neuro-plasticity to take place. The therapist distinguish specific movements and positions that provoke symptoms, then ask the individual to expose oneself to a mild to moderate level of dizziness in these movements. Movements should be done quickly to provoke moderate symptoms with a small rest between exercises to allow symptoms to diminish.[11-13]
- Symptoms of postural instability and disequilibrium: the aim of the intervention was to improve postural stability and to reduce disequilibrium. The individual was asked to learn how to use the intact remaining vestibular information and to use the appropriate visual and somatosensory information in challenging situations.[11-13] Information from the vestibular, vision, and somatosensory systems are essential for normal postural control.[104] The central nervous system (CNS) has the ability to process information from the three sensory channels to provide postural control. The

CNS can up weight or down weight inputs from any of the three sensory systems when there is any distortion of postural control.[104]

- Symptoms of oscillopsia: the aim of the intervention was to solve this impairment. Anticipatory eye movement activities to teach the subject to successfully compensate for eye movements correctly by giving predictable eye movement tasks that help the individual to maintain better gaze stability.[103] The individuals were taught substitution strategies to facilitate central preprogramming and therefore teach the individual to use the same strategy in predictable head movement situations. However, central preprogramming may not be effective in situations when head movements are not predictable.[103]
- The use of eye head exercises encourage the use of saccadic and smooth pursuit movements to facilitate maintaining gaze stability.[13] Individuals may use these exercises to help stabilize the eyes.[103]
- The use of VOR x1 and x2 exercises improve residual vestibular function and complement that by adding compensatory cervical-ocular reflex (COR) strategies.[13] Some studies report that the COR can help gaze stability since sensory information from neck joints and muscles helps eyes produce slow phase movements opposite to head movements.[103]

3.1.4 Study protocol

Every subject had six treatment sessions in the VR grocery store over the course of 6 weeks. The treatment session lasted for one hour and included six trials of habituation training; each trial was 4 minutes duration. One of 2 physical therapists (SLW, PJS) was present for each session to ensure subject safety and guide the treatment session in the VRBT. During the treatment session in the VRBT, subjects were asked to push an instrumented grocery cart and walk on the treadmill in the grocery store. Over the 6 week period, subjects were exposed to more visually complex aisles depending on the subject's tolerance. The therapist asked the subject to locate products on the right and left, up and down the shelves as they ambulate, and the subject should respond verbally when they locate the product.

The subjects' tolerance to the virtual environments was assessed by recording their vital signs (blood pressure and pulse rate) and their Subjective Units of Discomfort (SUD, 0-100 range) before and after each trial. The investigators used the SUDs score to determine if subjects should move to a more complex or less complex aisle in the virtual grocery store environment. The session was stopped if the SUD score indicated that the subject was highly symptomatic. Scores of 0 indicated no discomfort and scores of 100 indicated maximum discomfort. Subjects were given home exercises for their dizziness and balance and asked to keep a daily exercise diary.

3.1.5 Typical outcomes of vestibular rehabilitation

Subjects enrolled in the study were examined before and after the intervention using self report measures and performance-based measures of functional balance, by a therapist who was blinded to the VRBT intervention.

3.1.5.1 Intervention outcome measures: Self report

The Activities-specific Balance Confidence scale (ABC) is a questionnaire used to measure the individual perceived level of balance confidence in a 16 daily living activities, with 16 questions.[240] Responses range from 0% to 100%, the lowest score indicates low confidence in balance and the highest score indicates high level of confidence.[240] The ABC was found to be reliable with elderly people (65-95 years) over a two-week period with $r = 0.92$ ($p < 0.001$) and to have high internal consistency (Cronbach = 0.96) with minimal detectable changes (MDC) ranging between 13% - 38%. [33, 240-243]

The Dizziness Handicap Inventory (DHI) is a validated scale that recorded the level of disability and handicap resulting from dizziness.[33] The DHI score ranges between 0% to 100% with the lowest score indicating low disability resulting from dizziness and the highest score indicating a high level of disability. The DHI scale has three subscales (physical, emotional, and functional). In this study I calculated the sum score of all DHI subscales. The test-retest reliability for the DHI was 0.97 and the internal consistency was 0.91. [33]

The Situational Characteristics Questionnaire (SCQ) is a validated questionnaire that has two parts (A and B).[244] Subjects rated situations that may elicit anxiety or discomfort for the subject in real life. The SCQ (part A) has shown its ability to distinguish individuals with vestibular dysfunction among individuals complaining of anxiety disorders.[245, 246] The SCQ (part A) test-retest reliability was $r = .66$ and internal consistency (Cronbach = 0.74 to 0.76).[246] The SCQ (part B) has shown its ability to identify people with vestibular disorders. It is more powerful in discriminating balance and hearing disorders than SCQ (part A), but it is not able to discriminate individuals with vestibular disorders among individuals complaining of anxiety. The SCQ (part B) test-retest reliability was $r = .87$. [245]

3.1.5.2 Intervention outcome measures: Performance

The Dynamic Gait Index (DGI) examined a person’s ability to perform different gait activities such as walking with head turns and avoiding obstacles.[247] The scale has 8 items with each item scored from 0 to 3 (0 means severe impairment, 3 means normal ability). The optimal score in the DGI is 24 and ≤ 19 the subject has high risk of falling.[248] The DGI has been found to be valid and highly reliable with people with vestibular dysfunction (kappa=.95).[247] The DGI had a moderate positive correlation with the ABC (r= .68) and had moderate negative correlations with the Timed Up and Go (TUG) (r = - .77).[249]

The Functional Gait Assessment (FGA) also measured balance control during walking.[250] The FGA has 10 walking tasks, 7 of which are from the Dynamic Gait Index and 3 are new tasks added by Wrisley et al to increase the challenge of the test to be more sensitive to small changes in balance control during walking.[250] The FGA total score is 30 with each item scored in an ordinal scale (0-3, 0 means severe impairment, 3 means normal performance). The FGA inter-rater reliability was found to be high with an ICC of .83.[250] Internal consistency of the FGA was good with Cronbach alpha = .81.[250] The FGA scores also highly correlated with other balance measures (with DGI r =.8, with TUG r = -.5, with number of falls r = -.66, and with the DHI r = -.64).[251] Fall risk has been defined with a score of ≤ 22.[252]

To record gait speed, subjects were asked to walk 6.1 meters at their comfortable speed 5 times, then their average speed was calculated. Gait speed had shown good correlation with falls and functional abilities.[253] Whitney et al (1994) found that people with vestibular disorders have low gait speed compared to healthy controls.[254]

The TUG required subjects to stand up from a chair, walk three meters, turn around, then walk back to the chair and sit. Subjects were timed for the task; subjects who score 13.5 seconds or more are at high risk of falling.[255] The TUG had good intra rater reliability and good inter rater reliability r= .93 and .96 respectively.[256] The TUG also correlated with other balance and self report measures.[249, 250]

The Sensory Organization Test (SOT) was used to record postural sway in 6 conditions related to various sensory inputs important for balance (vestibular, vision, and somatosensory input).[257] In this study we used the composite SOT score.

3.1.5.3 Within session symptom measures

Before and after each treatment session, subjects reported the amount of nausea, dizziness, headache, visual blurring, oculomotor stress, and disorientation using a visual analog scale (VAS) and simulator sickness questionnaire (SSQ). Subjects rated the severity of their nausea, headache, dizziness, and visual blurring using a Visual Analog Scale.[258] Subjects were asked to mark a 10-cm vertical line corresponding to the severity of symptoms. One end of the line represented no symptoms at all, and the other end represented as bad as the symptoms can be.

The Simulator Sickness Questionnaire (SSQ) was used to record the severity of 16 different symptoms across three subscales: nausea (general discomfort, increased salivation, stomach awareness, burping, sweating, nausea, and difficulty concentrating), oculomotor stress (general discomfort, blurred vision, headache, eyestrain, fatigue, difficulty focusing, and difficulty concentrating), and disorientation (dizzy eyes open, dizzy eyes closed, head fullness, vertigo, blurred vision, nausea, and difficulty focusing).[259, 260] For each item, a 0 was recorded if none of the component symptoms were present and a 1 was recorded if any degree of the symptom was present (mild, medium, or severe). The sum of the component scores for each subscale was computed.

3.1.6 Statistical analysis (Aim 1)

Aim 1: To examine the use of virtual reality based therapy as an intervention for individuals with vestibular disorders. The study examined the effect of a VRBT intervention on self report measures and performance measures to determine the immediate and long term (6 months) effect of VRBT on gait, balance, nausea, headache, dizziness and visual blurring symptoms.

3.1.6.1 Self-report and performance measures

RESEARCH QUESTION:

Is there a significant difference on self-report and performance measures among the assessment times (pre intervention, after 6 week intervention, and after 6 months follow up after the intervention)?

Dependent variable (DV): self-report and performance measures- interval/ ratio; Independent variable (IV): assessment time (3 levels)

ASSUMPTION OF NORMALITY WAS TESTED FOR THE FOLLOWING:

1- Normality: the distribution of the DVs (self report and performance measures) should be normally distributed within each time of testing (pre, post, 6 months follow up). Normality assumption was tested using the Shapiro-Wilk statistic.

2- Outliers: there should be no extreme scores within each time of assessment. Outliers were checked by examining histograms and Quantile- Quantile (Q-Q) plots.

3- Sphericity assumption: it included testing for homogeneity of variance and homogeneity of covariance.[261] Sphericity assumes that the variances of the DV (self report and performance measures) among the levels of the IV (assessment time) are the same.[261] Sphericity was tested using the Mauchly's test (χ^2 test with $df = \frac{J(J-1)}{2} - 1$, J is the IV leveles).[261] To adjust for a violation of assumption of sphericity, the Huynh-Feldt method was used to compute the magnitude of violation (epsilon Є) that was multiplied with degrees of freedom. If Є =1, then the assumption is met, and if the Є < 1, then the assumption is violated.

If the assumptions are met, a one way within subjects analysis of variance is performed on self-report and performance measures to test the effect of the intervention (before vs. after the 6 week intervention vs. after 6 months follow up after the intervention). If the main effect (F - test) is significant, a simple effect analysis is performed to provide specific comparisons between assessment times. In order to find the pattern of differences on self-report and performance measures among assessment times, post hoc pairwise comparisons are performed using the Bonferroni adjustment. Bonferroni adjustment is used to adjust for inflation of a type one error.

If the assumptions are not met, nonparametric statistics (distribution-free tests) are used. Both parametric and nonparametric statistics test hypotheses and use statistical ratio or test statistics. Both tests are evaluated using an alpha level significance. The parametric statistics are generally more powerful and considered more sensitive to identify significant differences for a given sample size.[262] The power efficiency differences between both types are because nonparametric statistics involve ranking scores rather than comparing the metric changes.[262] The nonparametric statistics uses rank ordering of scores from smallest to largest score rank. Rank 1 is given to the smallest score, and highest rank is equal to the sample size (n).

The Friedman two-way analysis of variance by ranks, a nonparametric test, was used to test the effect of the intervention on self-report and performance measures among assessment times (pre intervention, post 6 week intervention, and 6 month follow up). The Friedman ANOVA test is a powerful alternative test to parametric repeated measures ANOVA.[262] During the Friedman ANOVA test, scores are converted to ranks, and the ranking process is within each subject among assessment times. The Friedman ANOVA test uses χ^2. When χ^2 is significant, pairwise differences for multiple comparisons among assessment times are done using the Wilcoxon signed ranks test. The Wilcoxon signed ranks test was used to test the effect of the intervention on the self-report and performance measures before vs. after the 6 week intervention and before vs. after 6 months follow up. The Wilcoxon signed ranks test can evaluate the differences within paired scores and examine both the direction of difference and the relative amount of difference among assessment times.[262]

3.1.6.2 Within session symptom measures (VAS, SSQ)

Assumptions of normality and outliers were tested. If the assumptions are met, a 2 X 6 within-subjects analysis of variance are performed on VAS and SSQ as a function of test time (pre session, post session) and the 6 treatment sessions (session 1, 2, 3 , 4, 5, 6). The dependent variables (DV) were VAS and SSQ symptom measures, the 1st independent variable (IV) was test time (pre treatment session, post treatment session); the 2nd IV was the 6 treatment sessions. The following three research questions were answered:

- Is there a significant difference on the symptom measures (VAS, SSQ) among the 6 treatment sessions averaged across test time (pre, post)? (Main effect of treatment sessions: provide information about habituation success)
- Is there a significant difference on the symptom measures (VAS, SSQ) between pre and post every treatment session averaged across the 6 treatment sessions? (main effect of every single treatment session)
- Is the pattern of difference on the symptom measures (VAS, SSQ) among the 6 treatment sessions significantly different before vs. after each treatment session? (interaction effect)

If the assumptions are not met, nonparametric statistics are used to answer the following question: Is there a significant difference on VAS and SSQ scores before vs. after each treatment session? The Wilcoxon signed ranks test was used to measure the immediate effect of VRBT on VAS and SSQ subscales before vs. after each treatment session.

Also a nonparametric statistics were used to answer the following question: Is there a significant difference on VAS and SSQ post scores among treatment sessions? To measure the treatment-related effect of VRBT on VAS and SSQ scores, the post treatment VAS and SSQ scores were compared across the six visits using the Friedman test. For all analyses, the level of significance were set at $\alpha = 0.05$. Intention to treat analysis was used for subjects with missing data at the 6 months follow up.

To measure how dizziness severity (DHI) and space and motion sensitivity (SCQ-A, SCQ-B) at baseline may influence symptoms (VAS, SSQ) during treatment sessions, appropriate correlation coefficient between initial scores of the (DHI, SCQ-A, SCQ-B) and the average amount of change in VAS and SSQ during treatment sessions was calculated to investigate how dizziness severity and space and motion sensitivity may influence symptoms during treatment sessions.

3.1.7 Statistical analysis (Aim 2)

Aim 2: to determine the difference of self-report and performance measures between conventional therapy and virtual reality based therapy (VRBT) in persons with vestibular disorders.

Outcome measures included the Activities-specific Balance Confidence scale (ABC), the Dizziness Handicap Inventory (DHI), the Situational Characteristics Questionnaire (SCQ) part A and part B, the Visual Analog Scale (dizziness, headache, visual blurring, nausea), and the Simulator Sickness Questionnaire (SSQ). Performance measures included the Functional Gait Assessment (FGA), the Dynamic Gait Index (DGI), gait speed, the Timed Up and Go (TUG), and the Sensory Organization Test (SOT).

Assumptions of normality, outliers, homogeneity of variance, and homogeneity of covariance were tested. Compound symmetry for both (homogeneity of variance, and homogeneity of covariance) were tested using Box's M test with α =.001 since Box's M test is conservative.[261]

If the assumptions are met, a 2 X 3 mixed analysis of variance is performed on self-report and performance measures as a function of assessment time and intervention type. The within subjects independent variable was assessment time (pre, post, 6 month follow-up). The between subject independent variable was the intervention type (VRBT, conventional therapy). And the DV were self-report and performance measures. The following questions were answered:

- Is there a significant difference on self report and performance measures among the assessment times (pre intervention, after 6 week intervention, and after 6 months follow up after the intervention) averaged across intervention type (conventional therapy, VRBT)? (main effect of assessment time)
- Is there significant difference on self report and performance measures between the VRBT group and the conventional therapy group averaged across assessment times? (main effect of intervention type)
- Is the pattern of difference on self report and performance measures among assessment times significantly different between the VRBT and the conventional therapy? (interaction effect of assessment time and intervention type)

If the assumptions are not met, nonparametric statistics are used to answer the following question: Is there a significant difference on self report and performance measures among the assessment times (pre intervention, after 6 week intervention, and after 6 months follow up after the intervention) for both groups? Friedman ANOVA test was used to measure the significant difference for each group among assessment times, then pairwise differences for multiple comparisons among assessment times were done using the Wilcoxon signed ranks test. The Wilcoxon signed ranks test was used to test the effect of the intervention on the self-report and performance measures before vs. after the 6 week intervention and before vs. after 6 months follow up after the intervention.

Also nonparametric statistics were used to answer the following question: Is there significant difference on self report and performance measures between the VRBT group and the conventional therapy group among assessment times? Wilcoxon signed ranks test was used to compare intervention groups at pre 6-week intervention, post 6-week intervention, and at 6 month follow up.

3.2 THE USE OF THE BALANCE REHABILITATION UNIT IN BALANCE ASSESSMENT

3.2.1 Study design

This was an experimental-cross sectional study design. The psychometric properties (reliability and validity) of the Balance Rehabilitation Unit (BRU) in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders were examined. The BRU was compared with a standard objective measure of balance, Sensory Organization Test (SOT). Each subject was tested twice in the Balance Rehabilitation Unit and one time using SOT during the same visit.

3.2.2 Inclusion criteria

The study consisted of 90 (male and female) subjects; 30 subjects with vestibular disorders between the age of 18 to 85 who were referred by Dr. Joseph Furman because of vestibular disorders, 30 young healthy controls between the age of 18 and 50, and 30 older healthy controls between the age of 60 and 85 were included in the study. Subjects with vestibular disorders with complaints of dizziness, vertigo, balance problems, falls, or difficulty focusing were included in the study. A power analysis based on 3 trial averages of 20 second average sway (cm/sec) was conducted to determine the appropriate number of subjects to be tested for aim 3. An estimate of the number of subjects required to attain a power of 0.8 with alpha = 0.05 for the different factors was 30 in each group.

Exclusion criteria for all subjects included known pregnancy and the use of assistive devices for standing. Healthy control subjects should not have any symptoms of inner ear disorders such as complaints of dizziness, vertigo, or balance problems. Healthy controls were screened before testing to make sure that subjects did not have vestibular disorders with the screening procedures taking around 15-20 minutes. The principal investigator (KAA) screened subjects. The screening physical examinations included examinations of the following: 1) spontaneous nystagmus, 2) cranial nerves 3, 4, and 6 (H test), 3) Dix-Hallpike testing, 4) the roll test, 5) the horizontal Head shake test, and 6) the head thrust test (HTT).

3.2.3 Assessment devices

3.2.3.1 The Balance Rehabilitation Unit (BRU)

The BRU had an assessment module that uses a head mounted display and foam for balance assessment. The BRU measures COP sway area and sway velocity under 6 different conditions. The BRU comes with a balance platform, head mounted device that projects different visual environments, and a safety harness. Subjects were asked to stand on the balance platform wearing a light head mounted device and also wearing the safety harness attached to the ceiling to prevent falls. The harness was a vest with a strap that wraps around the legs. Testing conditions included: 1) condition 1 standing on a firm surface eyes open looking forward, 2) condition 2 standing on a firm surface with eyes closed, 3) condition 3 standing on a firm surface looking at a visual world room (basket ball gym) displayed in the head mounted goggles that sways with the subject, 4) condition 4 standing on foam eyes open looking forward to the wall, 5) condition 5 standing on a foam with eyes closed, and 6) condition 6 standing on a foam looking at the visual world displayed in the head mounted goggles that sway as the subject sways.

3.2.3.2 Sensory Organization Test

Sensory Organization Test, the Smart Equitest by Neurocom version, is an objective tool for measuring balance and performing the sensory organization test. Subjects stood on the balance platform that can move back and forth while wearing the safety harness attached to the ceiling to prevent falls. The platform is surrounded on three sides by panels that may sway with the subject. Testing conditions include: 1) standing on a firm surface eyes open looking forward, 2) standing on a firm surface with eyes closed, 3) standing on a firm surface with a moving wall in front of them that sways with the subject, 4) standing on a platform that pivots about the ankles with eyes open, 5) standing on a platform that pivots about the ankles with eyes closed, and 6) standing on a platform pivots about the ankles with eyes open with a moving wall in front of them that sways with the subject.

3.2.4 Study protocol

The individual group was recruited from Eye and Ear Institute, with the clinic nurse introducing the study to individuals during their initial history intake. If interested, a member of the study team discussed the study, obtained consent, and then screened for eligibility. Healthy controls were recruited through ads that were placed around the University of Pittsburgh, Duquesne University, Carnegie Mellon University, and Point Park University. Subjects from other balance research studies who had agreed to be contacted for future studies were contacted and screened for eligibility.

The primary investigator received training in the use of the BRU. The primary investigator travelled to Montevideo, Uruguay for a training program for 7 days to learn how to use the BRU and to see the important elements of the BRU assessment and rehabilitation therapy programs.

The study procedures were performed at the Eye and Ear Institute by the principal investigator for one (2 hours) visit. Each subject was tested twice in the Balance Rehabilitation Unit and had 15 minute breaks in between testing (to examine the test-retest reliability), and was tested one time on the SOT (to examine the validity) the same day. To minimize the "order effect" bias, the order of testing of the two devices was changed with every other subject. For both devices, every subject was tested in 6 conditions and had 3 trials/ condition, with 20 second/ trials.

3.2.5 Outcome measures

Posturography test results including magnitude of sway velocity were examined in both devices. COP sway area and sway velocity was measured every trial/condition in both devices. COM is a passive variable that represents the center of total body mass controlled by the balance systems; the vertical projection of COM onto the ground is called the COG. The common balance variable that has been used in many studies of balance is the position and velocity of COP (representing the center of distribution of the total force of body weight on the ground).[171] COP is an active variable that moves continuously in all directions and has been recorded in anteroposterior (A/P) and mediolateral (M/L) directions. The COP moves around the COM to keep the COG within the base of support.

Theoretically, the term COP is the application point of all forces applied by the feet to the ground. COP is calculated from the weight distribution over the Base of support and sampled at a certain frequency (50 Hz). The sampled COP is a group of paired values (COP in AP direction, COP in ML direction). The COP A/P and COP M/L were used to estimate the area where the COP is moving and the velocity of the COP movement. COP area was measured in cm^2. The area of the XY plane where the points are distributed was used to estimate COP area. The standard way to estimate this area is by adjusting an ellipse known as the ellipse of confidence at 95%. The statistical definition of this ellipse is that there is 95% confidence that the center of a population would be inside the ellipse and that COP area is the estimation of the area of the ellipse. The following standard formula will be used to calculate COP area:

$$Area = 2 * \pi * F_{0.05[2,N-2]} * \left(\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2\right)^{\frac{1}{2}}$$

F is the Fischer distribution at 95%, (2 and N-2 degrees of freedom); F will be taken at 50Hz and is equal to 3.

Sway Velocity is computed using this formula:

$$Dxy = \sum_{i=1}^{N-1} \sqrt{\left(CX_{i+1} - CX_i\right)^2 + \left(CY_{i+1} - CY_i\right)^2}$$
$$Vsw = Dxy / T$$

T is the duration of the trial, SV is sway velocity, is path length, COPap is the data distribution in the AP direction, and COP ml is the data distribution in the ML direction. A Butterworth low pass filter (4th order, 2Hz cutoff) was used in Matlab to calculate filtered sway velocity (FSV) to reduce noise.

Root mean square (RMS) was computed using the following:

$$RMSap = \sqrt{\frac{\sum_{i=1}^{n} COPapi^2}{n}} \qquad RMSml = \sqrt{\frac{\sum_{i=1}^{n} COPml\ i^2}{n}}$$

Peak to Peak (PTP) was calculated using the following:

$$PTPap = max\ (COPap) - min\ (COPap)$$

$$PTPml = max\ (COPml) - \ min\ (COPml)$$

Max (COPap) is the highest sway amplitude in the AP direction, Min (COPap) is the lowest sway amplitude in the AP direction, Max (COPml) is the highest sway amplitude in the ML direction, and Min (COPml) is the lowest sway amplitude in the ML direction.

3.2.6 Statistical analysis (Aim 3)

Aim 3: To examine the test-retest reliability of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders by examining balance twice in every subject.

The usefulness of the BRU in measuring balance depends on the extent to which we can rely on its data. Measuring reliability of the BRU and its consistency and the error associated with testing is the first prerequisite for the BRU to be a useful tool for balance assessment. Without testing BRU reliability, we cannot have confidence that the data that is collected from the BRU is accurate. Random errors may occur due to chance, inattention, or unpredictable sources of measurement error and may affect reliability. The study protocol was detailed and specific enough to ensure consistent testing. Sources of error that may affect reliability were addressed in the study. Tracing paper was used between testing to track feet position for every subject to control changes in the distance between feet during test retest. Subjects were given enough time between test and retest to rest, plus they were given a break during testing any time they feel fatigue during standing.

Test-retest reliability, the stability of the BRU to obtain reliable results with repeated administrations, was investigated. The time interval between tests was considered carefully with testing far enough apart to avoid fatigue but also close enough (same day) to avoid big changes in balance and dizziness.

Correlation between test and retest may not be enough to measure reliability of the BRU. The correlation describes how the scores vary together but it does not describe the agreement between the two tests. Using a correlation coefficient, only two ratings can be correlated at one time; subjects were tested three trials/ condition. The variance component due to a true difference cannot be separated from the variance due to error using correlations.

Another method to test reliability of the BRU is to use both correlation and a t-test together to assess consistency and average agreement between test and retest. This method addresses the interpretation of agreement. However, we did not use this method since it does not provide a single index to describe and interpret reliability, and would be difficult to interpret.

An interclass correlation coefficient (ICC) was used to investigate reliability between test and retest because an ICC considers both correlation and agreement and provides a single index to describe reliability. The ICC uses variance estimates using analysis of variance (ANOVA), and it can assess the reliability among more than 2 readings. The ICC considers the differences between observed scores that are due to variations of the measurement system including factors related to the testing environment and subjects conditions, and not only as true score variance and random error.

The purpose and design of this study involved the use of the same rater representing only raters of interest, with no intention of generalizing findings beyond the raters involved. The rater was considered a fixed factor and not randomly selected in this design. Inter class correlation coefficient model 3 was the appropriate ICC to be used for this study. The form of measurement involved a single measurement, form (1). For relative reliability, the intra-class correlation coefficient, ICC (3, 1) and 95% CI was used to describe the level of agreement between test and retest.

For absolute reliability, average mean difference between trials with confidence limits, the standard error of mean (SEM), and the Bland and Altman method were used to describe the extent to which a balance score varies on test-retest measurements.[263-268]

A Bland Altman plot were used to graph the difference of each pair of measures, the mean difference, and the confidence limits on the vertical against the average of the two ratings on the horizontal. The Bland Altman plot described the following 1) overall the degree of agreement and whether the agreement was related to the value of the balance measure, 2) identification of bias and outliers, 3) visual illustration of the relationship between the mean and variance of the measurement scores, and 4) offered a supplemental way to the ICC for assessing reliability in clinical research.

The SEM was used to investigate whether the change in test scores in the study subjects was real. The smaller the SEM indicates a more reliable and useful measure of balance.

3.2.7 Statistical analysis (Aim 4)

Aim 4: To examine the convergent validity of the Balance Rehabilitation Unit in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders by comparing the results of the Balance Rehabilitation Unit with the results of SOT.

In convergent validity we examined the degree to which the BRU was similar to the SOT in measuring sensory organization for balance. Convergent validity was computed using an appropriate correlation coefficient between the BRU and the SOT measures of posturography.

RESEARCH QUESTION

Is there a significant association in sway measures between the BRU assessment module and the Equi-test™ SOT among the study sample (young healthy, old healthy, individuals with vestibular disorders)?

HYPOTHESIS

$H_0 : \rho = 0$ There is no correlation between the two devices.

Assumptions of normality and linearity were tested by examining scatter plots. If the assumptions are met, parametric statistics such as Pearson product-moment correlation is used to measure the correlation between the scores of the two devices. If the assumptions are not met, nonparametric statistics such as Spearman rank order correlation is used to test the correlation between scores in the two devices.

3.2.8 Statistical analysis (Aim 5)

Aim 5: To examine group differences among the study groups (young healthy vs. old healthy vs. individuals with vestibular disorders) in the six balance conditions of testing using the BRU and the SOT.

A one-way ANOVA (group effect) on sway for the simple comparisons and group as the only between subject effect (the repeated measures across the within subject effect of sensory conditions on sway) was used.

4.0 THE USE OF VIRTUAL REALITY BASED THERAPY FOR PEOPLE WITH BALANCE AND VESTIBULAR DISORDERS: THE PITTSBURGH EXPERIENCE

4.1 INTRODUCTION

Virtual reality based therapy has frequently been used in the treatments of motor or psychological dysfunction.[269, 270] Virtual reality based therapy may also demonstrate promise in people with sensory disorders, including vestibular dysfunction. The purpose of this paper is to describe how our experiments with virtual reality based therapy in the treatment in people with vestibular disorders have evolved and to provide you with some of our recent insights as to how effective virtual reality based therapy use can be in people with complaints of dizziness and balance loss.

Vestibular sensation is one of the three main sensory modalities for balance control. The other two senses include somatosensation (the feeling in the feet and extremities) and vision. With vestibular injury, vision is often affected because input from the vestibular organs in the inner ear drives eye movement via the vestibulo-ocular reflex (VOR). Usually after a peripheral vestibular event, there is a drop in the gain of the VOR (the ratio of the eye velocity to the head velocity).[271-273] As a result, people with vestibular disorders may complain of things jumping in their visual field (oscillopsia) or visual blurring.[274] They have difficulty focusing on objects when their head is moving, especially if they look away from the side of the injured ear, and their balance is disrupted. Difficulties with vision can last for longer than the acute phase of vestibular injury (a few weeks) and some individuals continue to complain of visual blurring with head movement for months or even years.[86] In addition to the complaints of visual blurring, dizziness results from head movements. Consequently, many individuals with vestibular disorders are afraid to move their heads, and they start to move less and can become sedentary.[274, 275]

The use of virtual reality based therapy may be beneficial for addressing the vision-related symptoms and restriction in head movement caused by vestibular disorders. Recovery of the gain of the VOR requires visual inputs and active head movement,[14, 276] both of which can be encouraged and monitored with the use of virtual reality based therapy. Viirre [277] and Kramer et al [278] were the first to attempt to use virtual reality based therapy for people with vestibular disorders. Viirre and Sitarz [14] demonstrated that virtual reality based therapy training can induce adaptations in the VOR and reduce dizziness.

Vestibular disorders may also activate anxiety pathways which can significantly affect outcome of people with vestibular loss.[65, 279-284] For example, Jacob et al[80] and Bronstein [81] have both reported that people with vestibular disorders can experience increased dizziness and anxiety in visual environments that consist of complex textures and motion, such as large grocery stores, stores that have many small products or even stores that have high contrast floors.[285]

Consequently, virtual reality based therapy may be used by the therapist as a form of habituation or exposure therapy.[14] These methods are similar to what is often called exposure therapy that has been used effectively for the treatment of anxiety disorders, such as fear of heights, fear of flying, and for post-traumatic stress disorder.[65, 270, 279, 283, 286-289] By repeatedly exposing individuals to the stimuli that cause the symptoms, there is an attempt to decrease symptoms via central nervous system compensation.[279] The advantage of a virtual environment is that one can expose the individual to environments that match the individuals experience and also one can easily dose the treatment.

Our goal at the University of Pittsburgh has been to develop a systematic way of evaluating the safety and efficacy of using virtual reality based therapy for treatment of people with vestibular disorders. In the remainder of this article, we will report on our findings in three experiments that we have conducted in our three screen, wide field of view (FOV) environment (BNAVE: Balance NAVE Automatic Virtual Environment). In all cases the physical structure for displaying the virtual environment was the same, although different software platforms have been used to generate and the environments. Three 2.4 m X 1.8 m (vertical X horizontal) back-projected screens are arranged as shown in **Figures 4.1 and 4.2**. The side screens make an included angle of 110^{o} with the front screen. The front screen is 1.5 m from the user, and the opening of the structure at the location of the subject is approximately 2.9 m. The images are displayed using Epson 810p PowerLite LCD monoscopic projectors, with a pixel resolution of 1024 X 768 for each screen. Each projector is connected to an NVIDIA GeForce4 graphics processing unit (64 MB texture memory) installed in a separate PC (Pentium, 2.2 GHz, 512 MB RAM) running Windows 2000. The movement of the images on the three PCs is synchronized and controlled by a server via a local area network. The update rate of the images is consistently at least 30 frames per second.

4.2 EXPERIMENT 1

Goal: We first examined the degree of simulator sickness in participants with and without vestibular disorders as they performed coordinated gaze shifts in different optic flow fields.[290, 291] The primary goal of this experiment was to determine if participants could tolerate making head movements in a virtual environment, using outcome measures of simulator sickness and discomfort.

Participants: Seven participants with unilateral vestibular hypofunction (UVH) and 25 control participants participated. The mean age was 53 years (range 27-77 years) for the participants with UVH and 52 years (range 22-83 years) for the control participants.

Protocol: Participants were tested on 6 visits, during which they performed the same coordinated gaze shifts with a different optic flow background on each visit. The optic flow fields consisted of light and dark stripes moving toward the subject from the front, with different levels of contrast and spatial frequency. During the high contrast conditions, the luminance of the stripes was 1 and 170 cd/m^2 (candelas per square meter) respectively. During the low contrast conditions, the luminance of the stripes was 15 and 34 cd/m^2. The low contrast condition was based on average measurements of luminance obtained from products sampled at a local grocery store, using a luminance meter (LS-100 Luminance Light Meter, Minolta Corp. Ramsey, NJ). The spatial frequencies were set according to common sizes of soup cans (high, 4.2 cycles/meter) and cereal boxes (low, 1.4 cycles/meter) found in the local grocery store.

Prior to the first trial and after every trial during the rest break, the Subjective Units of Discomfort (SUDS, 0-100 range) was rated according to how much "anxiety" the subject perceived during the trial. In addition, the Simulator Sickness Questionnaire (SSQ) was completed.[260] The SSQ contains 16 items on which participants rate the degree of particular symptoms on a 4-item severity scale (0=none, 1=slight, 2=moderate, 3=severe). The SSQ has three subscales that were comprised of the following symptom types: nausea (general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, burping), oculomotor stress (general discomfort, fatigue, headache, eyestrain, difficulty focusing, difficulty concentrating, blurred vision), and disorientation (difficulty focusing, nausea, head fullness, blurred vision, dizzy with eyes open, dizzy with eyes closed, vertigo).

Control participants rated their SUDS at 0 after 85% of the trials and rated items on the SSQ at zero greater than 90% of the time. As a result, computing the transformed scores as detailed by Kennedy et al. did not provide meaningful information.[260] Therefore, for examining SUDS and SSQ ratings, the number of non-zero scores were tabulated for each subject at baseline and after each of the 8 trials, for each of 6 visits (54 scores per subject). The effect of group on the number of non-zero scores was tested using the Mann-Whitney U test. Because of the low occurrence of symptoms in the control group, the effect of visit number, type of visual environment, and trial number during each visit on the symptom severity was examined only in the vestibular group. Furthermore, we investigated these factors for items that were rated greater than zero at least 20% of the time. Friedman two-way analysis of variance by ranks was used to investigate if the independent variables of visit number, the type of visual environment or the trial number during each visit had a significant effect on the number of non-zero scores for the SUDS and SSQ. An alpha = 0.05 was used to indicate significance.

<u>Results:</u> The percentage of trials in which participants had a symptom rating greater than zero is shown in **Table 3**. Control participants had non-zero SUDS scores in 15% of the trials and rated items on the SSQ above 0 less than 10% of the time. Participants with vestibular disease had a significantly higher proportion of non-zero responses for the SUDS and the

following items of the SSQ: fatigue, difficulty focusing, dizziness: eyes open, and dizziness: eyes closed. Two of these symptoms are components of the oculomotor stress subscale and three are components of the disorientation subscale.

The number of non-zero symptoms did not change significantly for any of the items during any particular visits or visual environment. However, there were increases in the number of non-zero ratings as a function of the trial number. Specifically, the ratings increased after the second trial for the following the items: SUDS, SSQ: general discomfort, difficulty focusing, and dizziness with eyes open.

Interpretation: Greater scores in the participants with vestibular disease can be explained, in part, by greater symptoms scores at baseline, i.e. before testing began. In addition, continued exposure to the environment during the visit resulted in increased symptoms in participants with vestibular disease. The increase in symptoms in participants with vestibular disease was not unexpected, and in our clinical experience, similar increases in symptom severity are commonly encountered during vestibular rehabilitation. No participants discontinued the study because of symptoms they experienced. As a result, we progressed to the next experiment in which participants with and without vestibular disease walked through one aisle of a virtual grocery store.

4.3 EXPERIMENT 2

Goal: The aim of the next study was to determine the change in symptoms induced in subjects while they ambulated through a long aisle of a virtual grocery store, while looking for products.[292] We wanted to examine if participants would be able to tolerate moving through the environment without having an increase in symptoms that would dissuade them from returning for additional visits.

<u>Participants:</u> Twenty healthy participants with no evidence of neurological disease (10 female, mean age 45 years, range 21 - 79 years) and 10 individuals with unilateral vestibular hypofunction, UVH (4 female, mean age 58 years, range 37 - 69 years) participated.

<u>Protocol:</u> Participants navigated down the aisle 6 times on each of 2 visits. On one visit, they navigated down the aisle by standing and pushing forward on a joystick; on the other visit they walked on a custom-made treadmill placed within the environment. During four of the 6 trials, participants were asked to search for common cereal boxes (Frosted Flakes and Cheerios) that had been pseudo-randomly placed 20 times along the length of a 120 m aisle. The aisle was a repeating pattern of shelves that were 5 m long with a 2 m inter-shelf break. The other parts of the aisle were completely filled with 30 other brands of products. On the other 2 trials, participants navigated down the aisle without searching for any products. Only one aisle was used because we did not want to induce any sensation of turning.

The speed of the treadmill was controlled by the amount of force participants exerted on an instrumented shopping cart. The speed of movement through the store was matched to the treadmill speed during the walking trials. During the standing trials, the speed of movement was controlled by pushing forward on the joystick. The maximum speed of movement of the treadmill and in the store was 1.2 m/s, based on maximum output produced by the treadmill motor. Each visit, participants underwent several practice trials to ensure that they were comfortable with the equipment and procedures. All participants were secured to an overhead harness to ensure that they were safe on the treadmill.

As in experiment 1, perceived anxiety was measured prior to testing and after each trial using the SUDS scale and participants completed the SSQ. A similar statistical analysis to that detailed in Experiment 1 was conducted. The number of symptoms that had an intensity greater than 0 for the SSQ was computed for each of the 6 trials. The scores from both measures were not normally distributed; in particular, there were a large number of trials in which the SUD was 0, and no symptoms were reported on the SSQ. Therefore, differences in SUD and SSQ between healthy controls and participants with UVH were examined with the non-parametric Mann-Whitney U test, using the median of each subject's scores as the estimate of central tendency. Between-visit (standing vs. walking) and between-trial differences (search vs. no search) were tested using the non-parametric Friedman test, again using the median of each subject's scores. An alpha = 0.05 was used to indicate significance.

<u>Results:</u> The prevalence of SUD ratings that were greater than zero during the testing demonstrated a large difference between controls and participants with UVH. After 81% of the trials, participants with UVH had a SUD score greater than zero, compared with 39% of the trials in controls. Participants with UVH had greater median SUD scores compared with controls during both the pre-test assessment and virtual reality based therapy exposure ($p = 0.002$). However, there was no difference in the change in SUD from pre-test to virtual reality based therapy exposure between the two subject groups. None of the experimental factors had a significant effect on SUD score, including the visit number, mode of locomotion (standing vs. walking), and search strategy.

The prevalence of SSQ ratings that were greater than zero during the testing also show group differences. After 81% of the trials, participants with UVH reported at least one symptom, compared with 29% of the trials in controls ($p<0.002$). As in Experiment 1, oculomotor and disorientation symptoms were more prevalent than nausea symptoms. The range of median number of symptoms reported by the participants with UVH was 0 to 12 out of 16. The range of median number of symptoms reported by control participants was 0 to 2 out of 16. The change in number of SSQ symptoms reported from pre-test to virtual reality based therapy exposure did not differ between the groups.

Interpretation: Participants with and without vestibular abnormalities were able to complete all trials when navigating through a virtual grocery store, except for one individual. She was unable to complete the final trial on her second visit due to nausea. Individuals with vestibular disorders reported more symptoms during the pre-test than the control participants. These remained relatively stable over the visit, suggesting that participants in both groups tolerated exposure to the virtual grocery store. Once safety was established, we decided to use a 16 aisle virtual grocery store to treat people with dizziness over a 6 week intervention.

4.4 EXPERIMENT 3

Goal: The purpose of the final study which is currently ongoing is to test the effectiveness of using the virtual reality based therapy in treating individuals with vestibular disorders.

Participants: Twelve participants with vestibular disorders (mean age 52 years, age 18 - 80 years) who complained of dizziness and loss of balance participated.

Protocol: Participants attended 6 treatment sessions over the course of 6 weeks. Six treatment sessions were used because it is in the range of the treatment duration reported in several studies, including retrospective studies reflective of clinical practice.[42, 293, 294] All participants were tested prior to and after the intervention using self-report measures and performance-based measures of functional balance. The self report measures included the Dizziness Handicap Inventory (DHI),[33] and the Activities-specific Balance Confidence Scale (ABC).[240] The Dizziness Handicap Inventory (DHI) is a validated tool used to asses the degree of handicap associated with dizziness. It has a range from 0 to 100, with higher scores indicating greater (worse) perceived handicap.[33] The Activities-specific Balance Confidence Scale (ABC) is a 16-item scale. Each item is rated from 0% (no confidence) to 100% (complete confidence) to assess balance confidence in daily activities. A score of 100 indicates the highest level of confidence that the individual will not lose the balance and scores of 0 indicate the most impairment.[240]

The performance-based measures included the Dynamic Gait Index (DGI),[295] Timed Up and Go (TUG),[296] and the Sensory Organization Test (SOT) of computerized dynamic posturogrpahy.[297] The DGI and TUG were used to determine the risk of falling [255, 298] and the Sensory Organization Test to assess the individual's ability to use the sensory information for their balance.

The subject began by standing on the treadmill and pushing the grocery cart. The speed of the treadmill and movement through the virtual grocery store increased linearly with the force in the anterior direction, up to a maximum speed of 1.2 m/s. Application of greater force by the left hand resulted in turning to the right, and vice versa, as if one were pushing a cart. During each treatment, the participants were asked to ambulate up and down the aisles at their comfortable speed 4 minutes at a time, 6 times per visit for a total exposure of 24 minutes per visit. All individuals were secured with an overhead safety harness during all trials. The store had 16 aisles where the visual contrast of the product textures and density of products in the greater numbered aisles. Participants were asked to continuously find different products by a physical therapist experienced in vestibular rehabilitation. Participants reported SUDS scores before and after each 4 minute trial. The therapist used the subject's SUDs scores to determine the aisle characteristics. For example, if symptoms increased substantially, they were asked to start in an "easier" aisle or if they experienced no difficulty, they were asked to walk and find products in an aisle that had greater contrast and product density.

The effect of the intervention on scores for all of the measures was tested using the Wilcoxon signed ranks test, with an $\alpha = 0.05$.

Results: At least two-thirds of the participants improved on all of the outcome measures except for the TUG (**Table 4**). The greatest improvement occurred for the self-report measures, indicating reduction in perceived dizziness handicap and improved confidence in their balance while performing daily activities.

Interpretation: Statistically significant improvements were found in four of the five measures, and the magnitude of change was comparable with improvements seen with conventional vestibular rehabilitation performed in our clinic.[97, 293] Although minimum detectable change (MDC) scores have not been firmly established on these measures for this population, the amount of improvement seen in this study is less than what has been reported in literature. The mean change in ABC of 14 compares favorably with MDCs ranging from 6 to 38% reported in the literature.[97, 243] However, mean changes in the DHI (15 points), DGI (2 points), and SOT (5 points), are less than reported MDCs of 18 for the DHI,[33] 4 for the DGI,[97] and 10 for the SOT.[299] A potential reason why the change was not as large in this study compared to others is that our sample of participants was less impaired compared with other studies.[97, 293] Despite improvement in the DGI, a gait measure that incorporates functional activities such as walking with head turns and stair climbing, the TUG, a measure related to gait speed, was unaffected, possibly because all subjects had TUG scores that were within normal limits at the initial evaluation.

4.5 CONCLUSION

The use of virtual reality based therapy for people with vestibular disorders appears promising. People with vestibular disease had a transient increase in symptoms in the optic flow and virtual environment,. Overall, individuals improve on both self-perception and objective measures of balance and postural control. Our next goal is to determine if virtual reality based therapy intervention is superior to results attained from conventional physical therapy treatment.

Despite the promise of the use of virtual reality based therapy for rehabilitation of people with vestibular disorders, there are several challenges that must be overcome to make it available on widespread basis. For one, the hardware and software used for virtual reality based therapy are continuously changing. We are using our second software package, and for each package, considerable time has been spent in development. In addition, we have changed used 2 different projector systems, 3 different personal computer systems. Each of these changes requires time to integrate. Furthermore, our current installation is probably cost and space prohibitive for most clinics to use. If we continue to demonstrate improvement in outcomes, our goal is to determine if the same improvements can be realized with equipment that requires less resources (e.g. a head mounted display or small display dome). We are confident that these challenges can be overcome.

4.6 ACKNOWLEDGEMENTS

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Table 3: The percentage of non-zero responses for the Subjective Units of Discomfort (SUDS) and the Simulator Sickness Questionnaire (SSQ)

Symptom Scale	**CON**	**VEST**	**P**
SUDS	15	60	0.01
SSQ			
General Discomfort (N, O)	10	41	0.08
Fatigue (O)	6	24	0.01
Headache (O)	6	10	0.09
Eyestrain (O)	10	12	0.08
Difficulty Focusing (O, D)	2	22	0.02
Increased Salivation (N)	0	2	0.79
Sweating (N)	1	3	0.82
Nausea (N, D)	1	14	0.79
Difficulty Concentrating (N, O)	1	16	0.37
Fullness of Head (D)	1	19	0.15
Blurred Vision (O, D)	1	15	0.05
Dizziness: Eyes Open (D)	3	51	0.01
Dizziness: Eyes Closed (D)	0	29	0.02
Vertigo (D)	0	3	0.42
Stomach Awareness (N)	1	15	0.56
Burping (N)	0	3	0.69

Given by controls (CON) and participants with vestibular disease (VEST), across all trials and visits. For each SSQ item, the subscales to which the item belongs is listed in parentheses (N: Nausea, O: Oculomotor stress, D: Disorientation).

Table 4: Mean scores of outcome measures taken before and after a 6 week virtual reality based therapy intervention for treatment of people with dizziness

Measure	Pre-treatment	Post-treatment	Change	#of participants improved	p-value
ABC	67 (22)	81 (14)	14 (19)	10/12	0.034
DHI	36 (16)	21 (14)	-15 (15)	11/12	0.008
DGI	20 (2)	22 (2)	2 (2)	8/12	0.031
SOT	63 (21)	68 (22)	5 (6)	9/12	0.027
TUG (s)	9.3 (1.4)	9.4 (1.4)	-0.1 (0.8)	5/12	0.638

p-values determined from Wilcoxon signed ranks test. ABC: Activities-specific Balance Confidence scale, DHI: Dizziness Handicap Inventory, DGI: Dynamic Gait Index, SOT: Sensory Organization Test, TUG: Timed Up and.

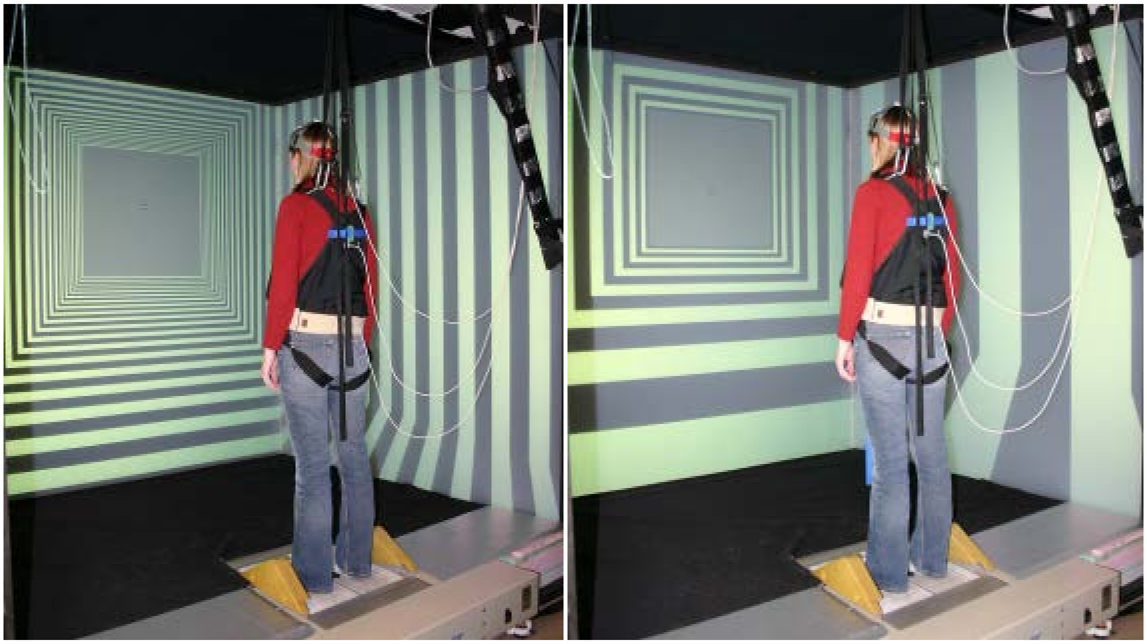

Figure 4-1: Participant standing in a wide field of view environment while viewing optic flow with high (left) and low (right) spatial frequency (Experiment 1)

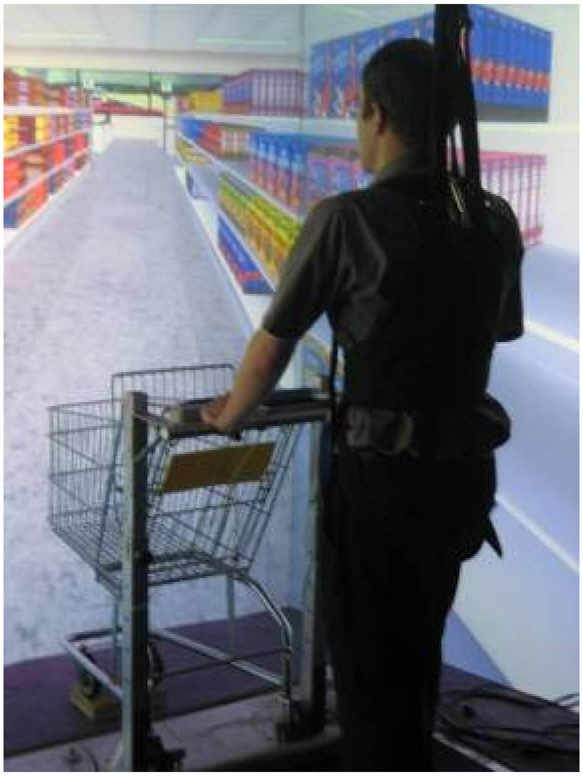

Figure 4-2: Participant walking through virtual grocery store while pushing on grocery cart instrumented with force transducers. The speed of the treadmill and movement through the store is proportional to the amount of force applied to the cart handle. See experiments 2 and 3 for details.

5.0 THE USE OF BALANCE NEAR AUTOMATIC VIRTUAL ENVIRONMENT IN THE TREATMENT OF VESTIBULAR DISORDERS

5.1 INTRODUCTION

Twenty to thirty percent of the general population have complaints of dizziness.[26, 27] Vertigo has a high negative impact on persons' quality of life, as 40% of individuals with vestibular disorders have interrupted daily activities, 41% take sick leave, and 19% avoid leaving their home because of their dizziness.[28] In addition, falls are significant problems associated with vestibular dysfunction that increase morbidity and mortality rates.[23, 300, 301]

People with vestibular disorders have complaints of dizziness, vertigo, balance problems, falls, and difficulty focusing.[1] They also may report blurred vision with activities requiring head movements while walking such as looking for products in shopping malls or reading signs while driving.[15, 81] Individuals with balance disorders may report increased symptoms in visually complex environments that have been described in the literature as "space and motion discomfort", "space phobia", "supermarket syndrome", "height vertigo", and "visual vertigo".[2, 4, 5] Situations that have been reported to precipitate space and motion discomfort or visual vertigo include: walking in supermarket aisles or shopping malls, large open areas, or complex and confusing visual stimuli.

Anxiety in the form of generalized anxiety or persistent agoraphobic symptoms is a common co-morbid condition in people with vestibular disorders.[55] Symptoms resulting from anxiety and vestibular disorders, including dizziness, nausea, or sweating have a large degree of overlap, and generally reflect activation of the autonomic nervous system. Moreover, people with dizziness who have greater autonomic symptomatology report greater handicap and recover less quickly.[69, 70] In some cases, fear of these symptoms may lead people with vestibular disorders to restrict or avoid activities that induce symptoms, which would have the unintended effect of delaying central compensation.[65, 279]

One of the most common interventions for individuals with vestibular disorders is vestibular rehabilitation, which reduces symptoms and improves balance problems in both young and older adults.[12, 98, 302] Vestibular rehabilitation attempts to (1) adapt the VOR gain, (2) improve gait stability, (3) correct overdependence on any specific sensory channel in postural control (e.g. either vision dependence, i.e. increased reliance on visual stimuli, or somatosensory dependence, i.e. increased reliance on somatosensory stimuli), (4) decrease anxiety from space and motion sensitivity, and (5) return the person to normal activities of daily living.[302] One of the treatment methods used to achieve these goals is through the use of habituation exercises.[303] Habituation exercises may be particularly helpful in combating the over-reliance on a sensory modality and reducing associated anxiety. Bronstein (2004) has suggested that in addition to customized vestibular rehabilitation, desensitizing individuals to visual motion and visuo-vestibular conflict may be of benefit to those who have visual vertigo. Furthermore, visually provocative habituation exercises have been shown to be useful during vestibular rehabilitation.[15, 82]

Virtual reality based therapy (VRBT) may be an ideal way to provide habituation exercises for individuals with vestibular disorders who become symptomatic in complex visual environments. The gradual exposures to the visual scenes may allow individuals to habituate to the provocative stimuli and help diminish symptoms. Using VR for exposure therapy has a well-established foundation in the treatment of specific phobias (e.g. fear of heights).[286, 288] The purpose of this study was to examine the use of virtual reality based therapy using the VRBT in the intervention of individuals with vestibular disorders. We explored the effect of a VRBT intervention on self report and performance measures to examine the immediate and long term (6 months) effect of VRBT on symptoms and balance function.

5.2 METHODS

5.2.1 Setting and participants

Twenty subjects were recruited from a vestibular disorders clinic after examination by a neurologist who specializes in balance disorders. The study was approved by the Institutional Review Board of the University of Pittsburgh. All subjects provided informed consent and agreed to participate in the study. The benefits and the risks of the study were explained to participants during the recruitment period and before the first treatment session.

Subject demographics and information about their vestibular disorder are described in Tables 5 and 6. The mean (SD) age of the subjects was 54 (10) years. The median duration of symptoms was 6.5 months. Thirteen subjects had peripheral vestibular abnormality, 4 subjects had mixed central and peripheral vestibular dysfunction, and 3 subjects had central vestibular dysfunction. The most common laboratory abnormalities were decreased gain, asymmetry on rotational chair testing, and abnormalities on vestibular-evoked myogenic potential testing.

5.2.2 Virtual reality based therapy environment

The virtual environment consisted of a grocery store modeled in 3D Studio Max and imported into Unreal Tournament (UT2004), as shown in Fig. 5-1, adapted for multi-screen environments with the Cave UT modification.[304] The BNAVE displays a store environment on three screens that surround the subject in a full-field CAVE-like environment. The store contains 16 aisles (20 m long) and has eight levels of visual complexity that depend on the spatial frequency and contrast of the product textures. The aisles increase in complexity from aisle one to aisle sixteen.[305]

Three 2.4 x 1.8 m (vertical X horizontal) back-projected screens are used. The side screens make an included angle of 110º with the front screen. The front screen is 1.5 m from the user, and the opening of the structure at the location of the subject is approximately 2.9 m. The images are displayed using Epson 810p PowerLite LCD monoscopic projectors, with a pixel resolution of 1024 X 768 for each screen. Each projector is connected to an NVIDIA GeForce4 graphics processing unit (64 MB texture memory) installed in a separate PC (Pentium, 2.2 GHz, 512 MB RAM) running Windows XP. The movement of the images on the three PCs is synchronized and controlled by a server via a local area network. The update rate of the images is consistently at least 30 frames per second.[305]

The virtual environment is interfaced to a custom-built treadmill with a maximum velocity of 1.2 m/s. At the front end of the treadmill is a grocery cart that is instrumented with two load cells on the push bar as shown in Fig. 5-2. The velocity of the treadmill and movement within the environment are coupled and proportional to the force applied to the cart.[305] Turning right and left is accomplished by pushing with more force on one side of the push bar vs. the other side.

5.2.3 Intervention

Every subject had six treatment sessions in the VRBT grocery store over the course of 6 weeks. The treatment session lasted approximately one hour and included six trials of virtual grocery shopping, each of four minutes duration. One of two physical therapists (SLW, PJS) was present for each session to ensure subject safety and guide the treatment session. During the treatment session, the subjects were asked to push the instrumented grocery cart while walking on the treadmill in the grocery store. Over the 6-week period, subjects were exposed to more visually complex aisles depending on the subject's tolerance. The therapist asked the subject to locate products on the right and left, up and down the shelves as they ambulated, and the subject responded verbally when they located the product.

The subjects' tolerance to the virtual environment was assessed by recording their vital signs (blood pressure and pulse rate) and their Subjective Units of Discomfort (SUD, 0-100 range) after each trial. The investigators also used the SUD score to determine if subjects should move to a more complex or less complex aisle, or stop the session if the SUD score indicated that the subject was highly symptomatic. Scores of 0 indicate no discomfort and scores of 100 indicate maximum discomfort. Table 7 demonstrates the treatment protocol. At the end of each treatment session, subjects were given home exercises for their dizziness and balance and asked to keep a daily exercise diary. Examples of home exercises provided to the individuals included: 1) standing exercises with/without head turns on firm or foam surfaces with feet apart, together, or in tandem position, 2) gait exercises with head turns right/left and up/down while walking forward, backward, tandem, around obstacles, or over obstacles, 3) gaze stabilization exercises VOR (X1) where the individual views a stationary object while turning the head side to side; exercises started with sitting, standing, then with walking in place on firm or foam surfaces, forward toward an object, backward away from an object, and tandem walking toward an object, 4) VOR (X2) where the target moves in the opposite direction of the head movement, and 5) otolith stimulation exercises that include head tilt in sitting, standing or walking.

5.2.4 Outcome measures

Subjects were examined before, one week after, and 6 months after the intervention using self-report and performance-based measures of functional balance by a physical therapist.

5.2.5 Self-report measures

The Activities-specific Balance Confidence scale (ABC) is a questionnaire used to measure the patient-perceived level of balance confidence in 16 activities of daily living.[240] Responses range from 0% to 100%, the lowest score indicates low confidence in balance and a higher score indicates high level of confidence.[240] The ABC is known to be reliable among older people aged 65-95 years over a two-week period with $r = 0.92$ ($p < 0.001$) and among individuals with vestibular disorders with an ICC range between .67 and .93 ($p < 0.05$) and Cronbach alpha = 0.95.[240, 306] The ABC minimal detectable change (MDC) ranges between 13% - 38% in older adults and persons with Parkinson’s disease.[240, 243] The ABC scale has high internal consistency, ranging between 0.8-0.97.[241, 243]

The Dizziness Handicap Inventory (DHI) is a validated scale that records the level of disability and handicap resulting from dizziness.[33] The DHI score ranges between 0% to 100% with the lowest score indicating low disability resulting from dizziness and the highest score indicating a high level of perceived disability. The DHI scale has three subscales (physical, emotional, and functional). In this study the sum score of all DHI subscales was calculated. The test-retest reliability for the DHI is 0.97 and the internal consistency is 0.91.[33]

The Situational Characteristics Questionnaire (SCQ) is a validated questionnaire that has two parts (A and B).[307] Subjects rate characteristics of situations that may elicit anxiety or discomfort for the subject in real life and make comparisons between the characteristics of the same situations. The SCQ (part A) has shown its ability to distinguish individuals with vestibular dysfunction among individuals complaining of anxiety disorders.[80, 307] The SCQ (part A) test-retest reliability is r = .66, and internal consistency is .74 to 76.[80] The SCQ (part B) has shown its ability to identify people with vestibular disorders. It is more powerful in discriminating balance and hearing disorders than SCQ (part A), but it is not able to discriminate individuals with vestibular disorders among individuals complaining of anxiety. The SCQ (part B) test-retest reliability is r =.87.[80]

5.2.6 Performance measures

The Dynamic Gait Index (DGI) examines a person's ability to perform various gait activities such as walking with head turns and avoiding obstacles.[247] The scale has 8 items; each item can be scored from 0 to 3 (0 means severe impairment, 3 means normal ability). The optimal score on the DGI is 24 and below 19 the subject has a high risk of falling.[248] The DGI has been found to be valid and highly reliable with people with vestibular dysfunction (kappa=.95).[247]

The Functional Gait Assessment (FGA) measures balance control during walking.[250] The FGA has 10 walking tasks, seven of which are from the Dynamic Gait Index and three are new tasks added to increase the challenge of the test to be more sensitive to small changes in balance control during walking.[250] The FGA total score is 30 with each item scored using an ordinal scale (0-3, 0 = severe impairment, 3 = normal performance). The FGA inter-rater reliability is high with an ICC of .83.[250] Internal consistency of the FGA is good with Cronbach alpha = .81.[250] The FGA scores are also highly correlated with other balance measures (with DGI r =.8, with TUG r = -.5, with number of falls r = -.66, with DHI r = -.64).[250] Scores of 22 or less have been related to fall risk in older adults.[252]

To record gait speed, subjects ambulated 6.1 meters at their comfortable speed 5 times, with their mean speed calculated. Gait speed has shown a good correlation with falls and mortality.[308]

The TUG requires subjects to rise from a chair, walk three meters, turn around, then walk back to the chair and sit. Subjects are timed during the task; subjects who score 13.5 seconds or greater are at higher risk of falling.[255] The TUG has good intra-rater reliability and good inter-rater reliability (r = .93 and .96) respectively.[256] The TUG also correlates with other balance and self report measures.[250]

The Sensory Organization Test (SOT) of the EquiTest is used to record postural sway in six conditions related to various sensory inputs important for balance (vestibular, vision, and somatosensory input).[192] In this study the composite SOT score was utilized.

5.2.7 Within-session symptom measures

Before and after each treatment session, subjects rated the severity of their nausea, headache, dizziness, and visual blurring using a visual analog scale (VAS).[258] Subjects were asked to mark a 10-cm vertical line corresponding to the severity of symptoms. One end of the line represents no symptoms, and the other end represents "as bad as it can be".

The Simulator Sickness Questionnaire (SSQ) was used to record the severity of 16 different symptoms across three subscales: nausea (general discomfort, increased salivation, stomach awareness, burping, sweating, nausea, and difficulty concentrating), oculomotor stress (general discomfort, blurred vision, headache, eyestrain, fatigue, difficulty focusing, and difficulty concentrating,), and disorientation (dizzy with eyes open, dizzy with eyes closed, head fullness, vertigo, blurred vision, nausea, and difficulty focusing).[259, 260] For each item, a 0 was recorded if none of the component symptoms were present and a 1 was recorded if any degree of the symptom was present (mild, medium, or severe). The sum of the component scores for each subscale was computed.

5.2.8 Statistical analysis

Four statistical analyses were conducted. First a repeated measures ANOVA was used to examine if the self-report and performance measures differed at one week after the intervention and at the 6 month follow-up, compared with before the intervention. All of the measures satisfied the assumption of being normally distributed. In cases of unequal variance, the Greenhouse-Geisser correction was applied. Post-hoc testing was performed using a Bonferroni correction with 2 planned comparisons and $\alpha = 0.025$. Intention to treat analysis was used for subjects with missing data at the 6 months follow up (4 subjects did not return).

Next we explored if a short-term change in symptoms (VAS and SSQ subscales) occurred from before the first trial to after the last trial within each session. To accomplish this, we used a repeated measures ANOVA for the measures that were normally distributed (Dizziness VAS, Nausea SSQ, Disorientation SSQ and Oculomotor SSQ). The main effects were within-session (2 levels: Pre, Post) and between-session (6 levels, Session 1 to 6). In addition, we wanted to determine if the amount of change differed across the six sessions by examining the interaction of the within- and between-session factors. For the measures that were not normally distributed (Nausea VAS, Headache VAS, and Visual Blurring VAS), the Wilcoxon signed ranks test was used to test for the effect of the short-term change on the average score before and after each treatment session. The Friedman test was used to determine if the change differed among the 6 sessions.

To measure the long-term habituation change effect of VRBT on VAS and SSQ scores, the post treatment VAS and SSQ scores were compared across the six sessions using a non-parametric Friedman test.

Finally, a Pearson correlation was performed between initial scores of the DHI, SCQ-A, SCQ-B and the average amount of change in VAS and SSQ during treatment sessions to investigate how dizziness handicap and space and motion sensitivity may influence symptoms during treatment sessions. For all analyses, the level of significance was set at $\alpha = 0.05$.

5.3 RESULTS

5.3.1 Self-report and performance measures

Table 8 presents the pretest scores, the posttest scores and the 6-month follow-up scores of self-report and performance measures for all subjects. At least 70% (14/20) of subjects demonstrated improvements in all self-report measures at the post-test and 6-month follow-up. After the intervention, subjects demonstrated significant improvement in the ABC ($p = 0.03$), DHI ($p = 0.004$), and SCQ-B scales ($p = 0.01$). At the 6-month follow up, subjects maintained their improvement in these self-report measures. For the performance measures, significant improvements were observed on the DGI ($p = 0.03$), and the SOT ($p = 0.012$), but not the FGA, gait speed and TUG. At the 6 month follow up, subjects preserved their recovery on the DGI and the SOT.

5.3.2 Within-session symptom measures

Figure 5-3 demonstrates changes in the VAS scores across all sessions. The dizziness VAS score increased significantly from pre-session to post-session ($p = 0.001$), but this increase did not differ among the six sessions ($p = 0.10$). Similarly nausea VAS ($p = 0.012$), headache VAS ($p = 0.039$), and visual blurring VAS ($p = 0.005$) increased during the session. However, the amount of change per session was not significantly different. Nausea, oculomotor stress, and disorientation SSQ scores showed a significant increase post-session compared with pre-session ($p < 0.001$). The amount of increase in the SSQ subscales within the session declined from the first session to the last session ($p < 0.05$ for all subscales), (Figure 5-4).

5.3.3 Long term habituation

To measure the overall effect of habituation to the environment, the post-session scores were compared from session one to session six. Dizziness VAS scores decreased significantly from 2.2 at the end of the first session to 0.5 at the end of the last session ($p = 0.03$, Figure 5-5). The visual blurring VAS scores decreased significantly from 1.1 at the first session to 0.2 at the 6th session ($p = 0.004$). Significant changes were not observed for nausea and headache VAS scores. There were significant decreases in nausea, oculomotor stress, and disorientation SSQ responses to the VRBT grocery store across treatment sessions (Figure 5-6). Nausea decreased from 2.4 to 1.5 ($p = 0.03$), oculomotor stress decreased from 4.0 to 1.7 ($p = 0.001$), and disorientation decreased from 3.7 to 1.5 ($p = 0.001$) respectively.

5.3.4 Relationship between initial self-report measures and within-treatment session symptom measures

Pearson correlations were performed between the self-report (DHI, SCQ-A, SCQ-B) initial scores and the average change in VAS and SSQ across all 6 treatment sessions to investigate how pre-treatment dizziness severity and space and motion sensitivity may influence symptoms during treatment sessions. Table 9 shows fair to moderate positive relationships between the initial scores of the SCQ-A , SCQ-B, and DHI with the amount of change in visual blurring VAS within treatment sessions, indicating that higher (worse) symptoms of visual blurring during the exposure to VRBT were related to greater levels of anxiety in environments that evoke visual and vestibular stimulation.

5.4 DISCUSSION

5.4.1 Self-report and performance measures

In this study we explored the effect of virtual reality based therapy intervention on self-report measures (ABC, DHI, SCQ A-B) and performance measures (FGA, DGI, gait speed, TUG, and SOT). Subjects improved significantly in 3 of the 4 self-report measures, 2 of the 5 performance measures, and maintained these improvements 6 months after the intervention ended. The amount of improvement was greatest for the self-report measures; in particular the effect sizes at the 6-month follow-up for the ABC and DHI were 0.70 and 0.60, respectively. In contrast, the effect sizes for the performance measures ranged from 0.12 to 0.50. It is possible that relatively limited improvement in the performance measures was found because many subjects were within normal limits at the time of the initial assessment. Gait speed (mean = 1.10) and TUG (mean = 9.2) are considered within normal limits for their age.[252, 298, 309-313] The DGI (mean = 21) and FGA (mean = 24) scores are considered higher than the cutoff points (DGI = 19, FGA = 22) associated with risk of falls and impairments of gait.[248, 252, 298, 314, 315] Although the amount of improvement in the ABC and DHI did not reach the level of minimum detectable change as reported in the literature (ABC: 22 pts (Powell and Myers, 1995), DHI: 18 pts (Jacobson and Newman, 1990)), the improvement was consistent with other trials of vestibular rehabilitation.[33, 95, 98, 240, 306]

5.4.2 Within-session symptom measures

Most of the subjects reported symptom increases during the training sessions. The dizziness VAS significantly increased in all sessions, and by the greatest amount compared with the other symptom ratings. Other measures that increased consistently during the sessions included visual blurring VAS and the nausea subscale of the SSQ. While the increase in symptoms may appear to be an unwanted and unintended side effect of the virtual reality based therapy intervention, it is a common occurrence in individuals who perform gaze stabilization, dynamic gait and static standing balance exercises that comprise standard vestibular rehabilitation interventions.[316] In fact, vestibular rehabilitation therapists routinely instruct their clients that an increase in symptoms is to be expected.[103, 316]

5.4.3 Long-term habituation

Analysis of the change in SSQ scores, as well as the post-session VAS and SSQ scores allowed us to examine how the subjects habituated to the intervention over the course of the 6 week intervention. The amount of increase in the reported nausea, oculomotor discomfort, and disorientation symptoms as reported on the SSQ was reduced from session 1 to session 6. A significant reduction in dizziness VAS from 2.2 to 0.5 and in visual blurring from 1.1 to 0.2 suggests that subjects were habituating to the virtual reality based therapy stimuli. Furthermore, all of the SSQ subscales measured at the end of the session decreased from session one to session 6. It is important to note that during this period, the intensity of the intervention progressed in terms of the simulated optic flow velocity perceived by the subjects during the locomotion through the store.

5.4.4 Relationship between initial self-report measures and within-treatment session symptom measures

The correlations between the initial DHI, SCQ-A and SCQ-B initial scores and the amount of change in VAS and SSQ during treatment sessions indicated that people with high dizziness handicap and space and motion discomfort also report greater problems with visual blurring. Jacob et al (Jacob et al 1993) suggested that the SCQ-A was a possible marker for vestibular dysfunction.[80] Higher scores (worse) on the SCQ-A and SCQ-B indicate that persons have greater discomfort or anxiety performing normal activities such as shopping, riding in a car or bus, in movie theaters, on escalators or elevators, and in the shower. Having greater difficulty with the above functional activities was related to our subject's reported headaches, dizziness and visual blurring, possibly suggesting that when individuals have symptoms, they are more functionally limited in their activities and ability to participate.

The current study extends the work of previous groups that have used technology-based visual stimuli for habituation of dizziness symptoms. One of the first studies delivered optokinetic stimulation in horizontal and vertical directions to individuals who had unilateral and bilateral vestibular disease.[82] The subjects were no longer symptomatic after an average of 8 sessions lasting 15 minutes, and posturography scores were improved. Viirre and Sitarz (2002) attempted to induce vestibulo-ocular reflex (VOR) gain adaptation in subjects with chronic dizziness, by having subjects search for objects within a panoramic scene displayed using a head mounted display (HMD).[14] After 10 sessions lasting up to 30 minutes, the subjects did increase their VOR gain, in contrast with subjects who did not receive the intervention. Pavlou et al. (2004) studied 2 groups of subjects with chronic dizziness; one group received custom vestibular rehabilitation and the other group received custom vestibular rehabilitation in combination with exposure to moving visual displays.[15] Significant improvement was demonstrated in both groups over the course of 8 weeks (16 sessions), but the subjects who received the additional visual-based treatment made greater improvements, in particular with space and motion discomfort. More recently, Suarez et al (2006) reported on using an HMD to display panoramic images for optokinetic stimulation, and visuo-vestibular interaction in older subjects with balance disorders. At the end of the six-week, daily intervention subjects demonstrated reduced sway.[317]

Several notable differences exist between the previous studies using technology-based habituation therapy and the current study. Foremost, rather than relying primarily on optokinetic stimulation, the virtual grocery environment was designed with the intent of increased subject interaction with the environment. To this end, the environment was based on a situation in which individuals with vestibular disorders commonly report increased symptoms. In fact, several questionnaires (Dizziness Handicap Inventory (Powell and Myers, 1995, Situational Characteristics Questionnaire, Jacob et al., 1993, Vestibular Activities of Daily Living, Cohen and Kimball, 2000) include walking in a grocery store as an item. Also, the subjects performed a functional task within the environment, by walking and moving their head to search for products that they would encounter in a real grocery store. In vestibular rehabilitation, individuals are encouraged to move their head during daily activities because movement is needed for adaptation and reweighting of the sensory signals.[318] In addition, as subjects ambulated, they pushed on a haptic grocery cart. This served two important purposes. For one, it allowed subjects to control the speed of their interaction with the virtual environment. Secondly, it allowed them to interact with the environment in a natural way. All of these factors would presumably enhance the subjects' sense of presence, which may allow them to more effectively habituate to the stimuli that cause the increased symptoms.[319, 320]

5.4.5 Limitation and future work

The study is a non-randomized cohort study that has no control group. As seen in Table 5, the duration of symptoms was beyond the acute stage (often greater than 6 months), and rotational chair abnormalities suggest that at least half of the subjects were not compensated. Consequently, we believe that improvements made were due to the intervention and not passage of time. Future work will include the comparison with conventional vestibular rehabilitation. Home exercises provided to the subjects by the end of each treatment session may also have helped in the improvement of the subjects. Examination of the type of dysfunction (peripheral, central or mixed) did not reveal any strong relationship between the magnitude of improvement and site of dysfunction, therefore, we are unable to state a relative benefit in any one type of diagnostic category.

5.4.6 Conclusion

Virtual reality based therapy (VRBT) may be a promising new intervention for individuals with vestibular disorders. The VRBT grocery store can be used as a habituation technique for individuals with vestibular and balance problems and may reduce vestibular symptoms and improve gait and balance.

Table 5: Characteristics of subjects at baseline concerning age, gender, duration of symptoms, and laboratory tests (oculomotor testing, positional testing, calorics testing, rotational chair testing, and vestibular-evoked myogenic potentials (VEMPs)) (n = 20)

Age (y)	
Mean SD	54 ±10
Range	27-70
Gender	14 Female, 6 Male
Duration of symptoms	
Median	6.5
Mean SD	5 ± 4
Range	1-16
Abnormal laboratory testing (n)	
Oculomotor	2
Positional	6
Calorics (reduced vestibular response)	6
Rotational Chair (decreased gain, asymmetry)	10
VEMPs	9

Table 6: Diagnosis, localization of the affected side, and duration of symptoms

ID	Diagnosis	Location of dysfunction	Side	Duration of symptoms (months)
1	Mal de debarquement; migraine-related dizziness	Mixed	Right	4
2	Vestibular neuritis; VOR asymmetry	Peripheral	Right	10
3	Posterior Canal BPPV cupulolithiasis	Peripheral	Left	7
4	Vestibular Hypofunction	Peripheral	Left	Unknown
5	Central suppression of vestibular sensitivity	Peripheral	Right	2
6	Post traumatic balance disorder	Central		4
7	Migraine-related dizziness, possible Meniere's Disease	Mixed	Left	6
8	Meniere's Disease	Peripheral	Right	28
9	Diabetes complication	Peripheral	Left	18
10	Migraine-related dizziness	Central		1
11	Meniere's Disease	Peripheral	Bilateral	1
12	Vestibular hypofunction; migraine-anxiety related dizziness	Mixed	Left	8
13	Dizziness of uncertain etiology; anxiety; VOR asymmetry	Central		8
14	Migraine-anxiety related dizziness vestibular hypofunction	Peripheral	Right	12
15	VOR asymmetry	Peripheral	Unknown	2
16	Peripheral vestibular hypofunction	Peripheral	Right	3
17	Vestibular hypofunction; migraine-related dizziness	Mixed	Left	9
18	Vestibular neuritis	Peripheral	Left	6
19	Superior vestibular neuritis	Peripheral	Right	4
20	Unknown etiology / VOR asymmetry	Peripheral	Unknown	1

VOR: vestibular ocular reflex; BPPV: Benign Paroxysmal Positional Vertigo.

Table 7: A summary of the treatment protocol from baseline assessment to the post-treatment follow up assessment

Week 0 **Pre-treatment assessment**	Self-report measures: ABC, DHI, SCQ-A, SCQ-B Performance measures: FGA, DGI, gait speed, TUG, SOT
Week 1 to 6 **VRBT session 1 to 6**	VAS and SSQ ratings before and after each treatment session SUD ratings before and after each of the 6 (4 minutes) trials
Week 7 **Post-treatment assessment**	Self-report measures: ABC, DHI, SCQ-A, SCQ-B Performance measures: FGA, DGI, gait speed, TUG, SOT
6-month follow-up **assessment**	Self-report measures: ABC, DHI, SCQ-A, SCQ-B Performance measures: FGA, DGI, gait speed, TUG, SOT

ABC: Activities-Specific Confidence scale; DHI: Dizziness Handicap Inventory; SCQ-A: Situational Characteristics Questionnaire part A; SCQ-B: Situational Characteristics Questionnaire part B; FGA: Functional Gait Assessment; DGI: Dynamic Gait Index; TUG: Timed Up and Go; SOT: Sensory Organization test; VAS: Visual Analog Scale for dizziness, headache, visual blurring, and nausea; SSQ: Simulator Sickness Questionnaire; SUD: Subjective Units of Discomfort.

Table 8: Self-report and performance measures (mean ± SD) for pre-treatment vs. post-treatment vs. 6-month follow-up

Outcome measure	Pre	Post	6-month follow-up	p value (Pre v. Post)	p value (Pre v. 6-month follow-up)
Self-report measures:					
ABC	66 ± 20	77 ± 19	81 ± 15	**0.031**	**0.009**
DHI	37 ± 17	25 ± 18	25 ± 16	**0.004**	**0.007**
SCQ part A	4 ± 3	3 ± 2	4 ± 3	NS	NS
SCQ part B	20 ± 12	13 ± 9	13 ± 9	**0.014**	**0.027**
Performance measures:					
FGA	24 ± 6	25 ± 3	25 ± 4	NS	NS
DGI	21 ± 2	22 ± 1	22 ± 2	**.03**	**0.02**
Gait speed	1.13 ± .17	1.14 ± .13	1.13 ± .15	NS	NS
TUG	9.0 ± 1.6	9.1 ± 1.3	9.3 ± 1.5	NS	NS
SOT	63 ± 18	68 ± 19	69 ± 17	**0.012**	**0.007**

Higher scores on the Activities-specific Balance Confidence scale (ABC), Functional Gait Assessment (FGA), Dynamic Gait Index (DGI), gait speed, and Sensory Organization Test (SOT) indicate better outcomes. Lower scores on the Dizziness Handicap Inventory (DHI), Timed Up and Go (TUG), and Situational Characteristics Questionnaire (SCQ) indicate better outcome.

Table 9: The Pearson correlation between the DHI, SCQ-A, and SCQ-B initial scores and amount of change in VAS and SSQ during treatment sessions. Positive correlations indicate that larger increases in VAS or SSQ scores during the session were associated with greater DHI and SCQ scores (i.e. worse) at baseline

The average change across all 6 treatment sessions / DHI, SCQ-A, and SCQ-B Pre scores			VAS Nausea	VAS Headache	VAS Dizziness	VAS Visual Blurring	SSQ Disorient-ation	SSQ Nausea	SSQ Oculomotor stress
Pearson correlation	DHI Pre	Pearson r	.189	.449	.380	.470	.076	.073	-.080
		p-value	.439	.054	.108	**.042**	.758	.765	.746
	SCQ-A Pre	Pearson r	-.041	.167	.298	.516	.114	.071	.286
		p-value	.871	.508	.238	**.028**	.652	.778	.250
	SCQ-B Pre	Pearson r	.031	.501	.332	.524	-.006	.116	-.150
		p-value	.900	**.029**	.165	**.021**	.981	.636	.541

Figure 5-1: Two aisles are shown in the VRBT grocery store with different products complexities on the shelves. The subject walks inside the store and looks for products called out by the physical therapist

Figure 5-2: The virtual environment is interfaced to a custom-built treadmill with a maximum velocity of 1.2 m/s. A grocery cart at the front end of the treadmill is instrumented with load cells on the push bar to control velocity and movement within the environment

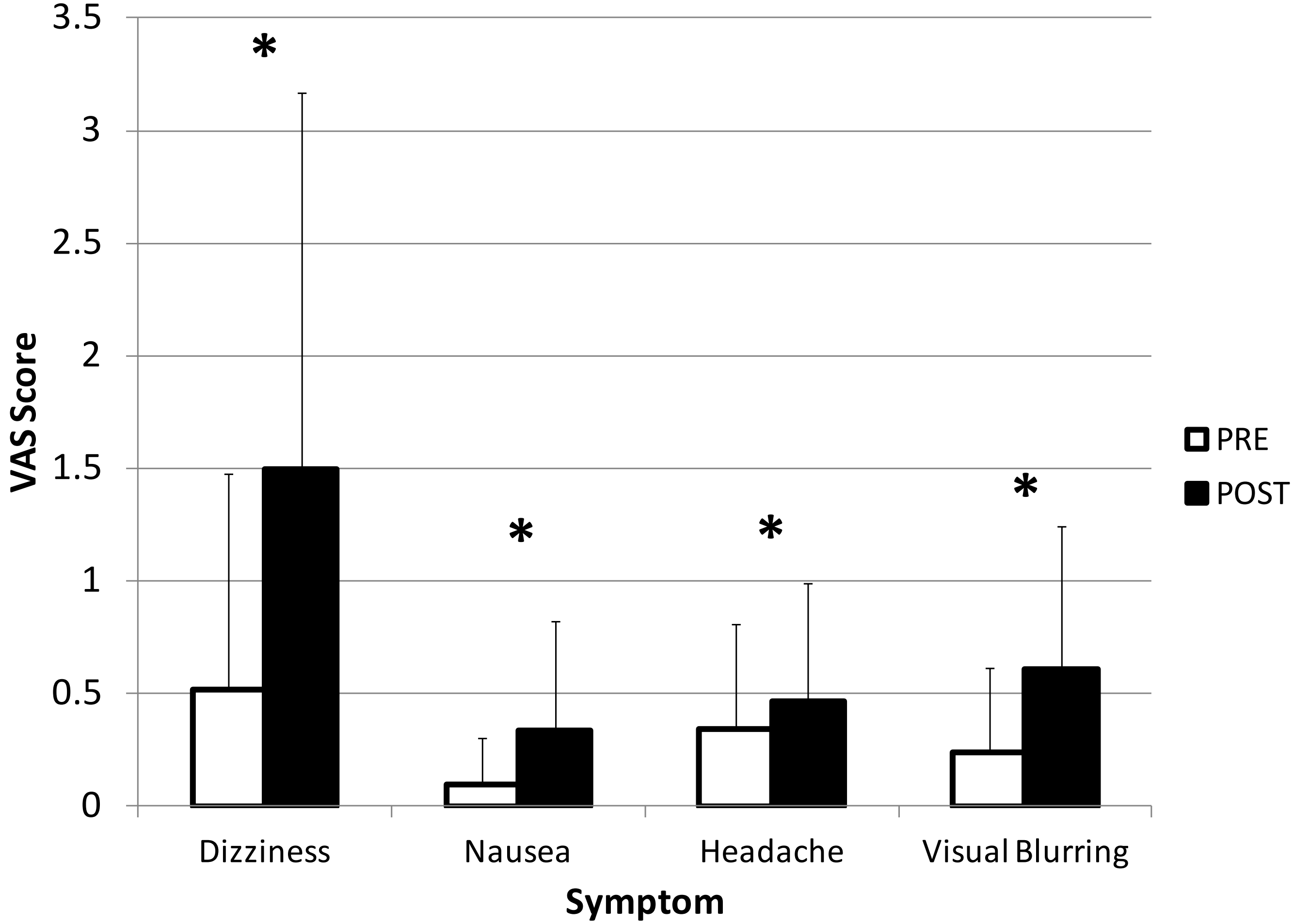

Figure 5-3: Mean ± standard deviation of the Visual Analog Scale (VAS) dizziness, nausea, headache and visual blurring pre and after post the treatment session, averaged across all 6 sessions. * The difference between pre scores and post scores was significant ($p < 0.05$)

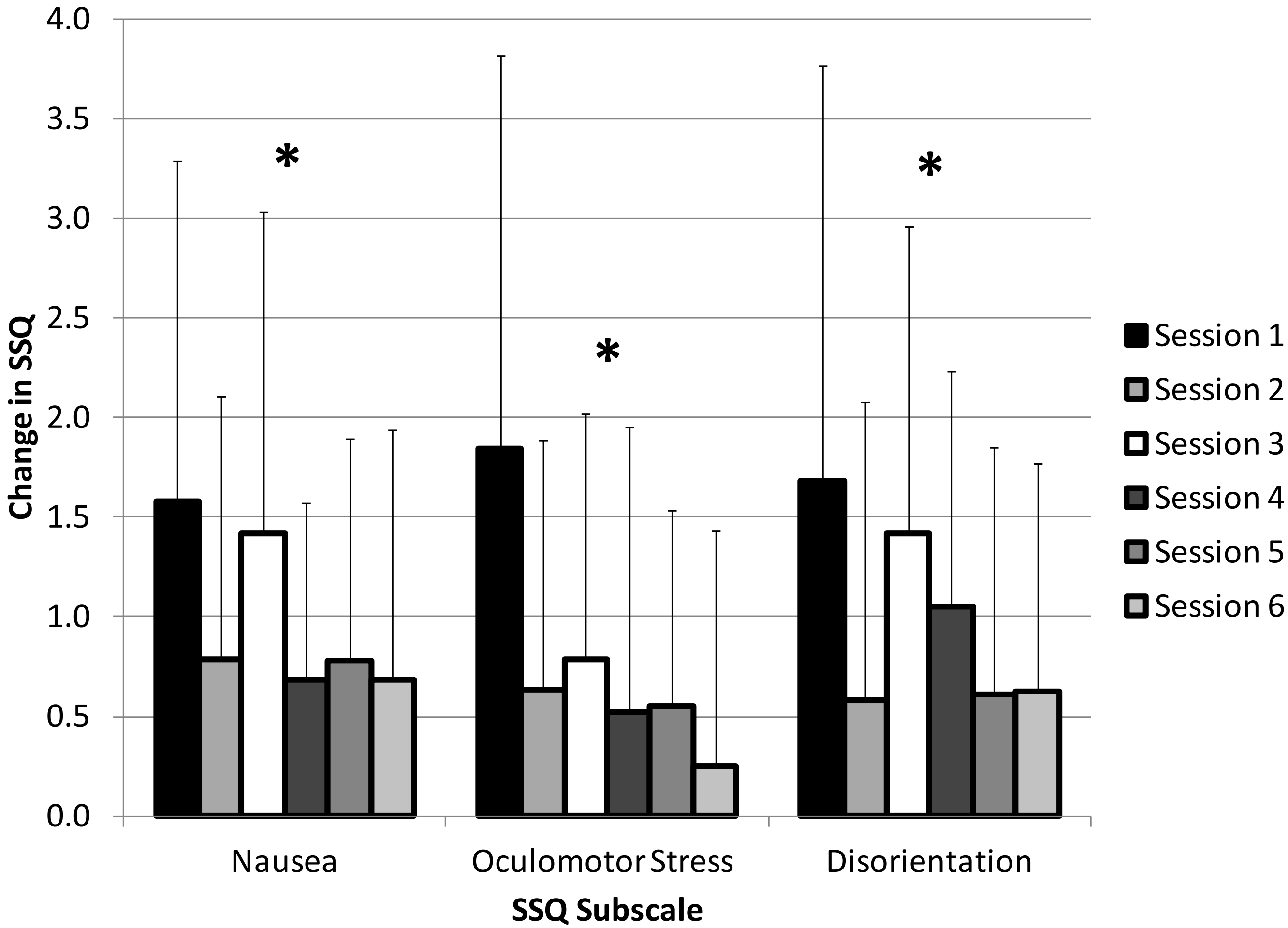

Figure 5-4: Mean ± standard deviation of the change in Simulator Sickness Questionnaire (SSQ) subscales (Nausea, oculomotor stress, and disorientation) from before to after the treatment session. * The linear trend for the reduction in the magnitude of the change was significant ($p < 0.05$)

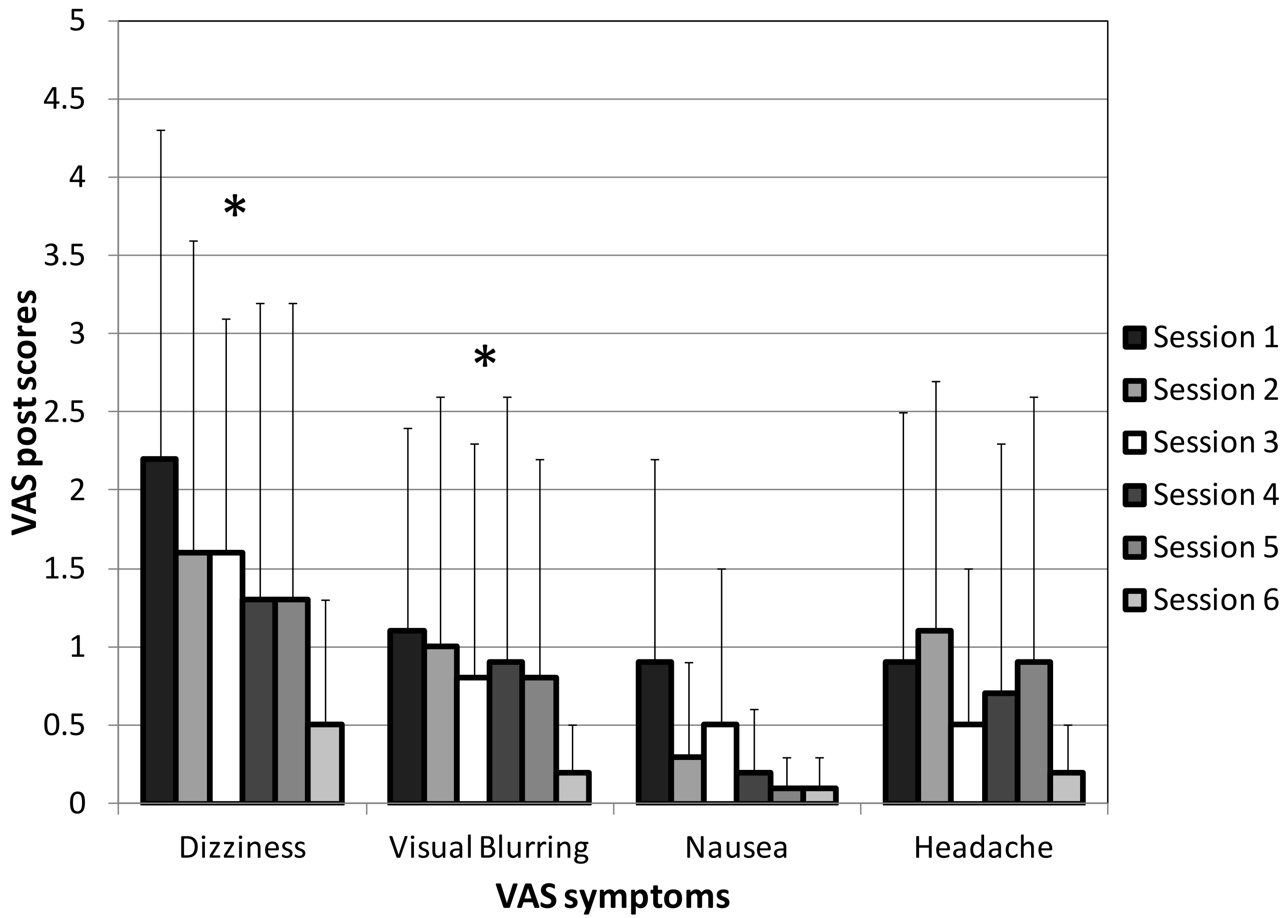

Figure 5-5: The Visual Analog Scale (VAS) post-treatment scores from session 1 to session 6. Dizziness and visual blurring scores lessened significantly across treatment sessions. * The non-parametric Friedman test for magnitude of the post scores was significant ($p < 0.05$)

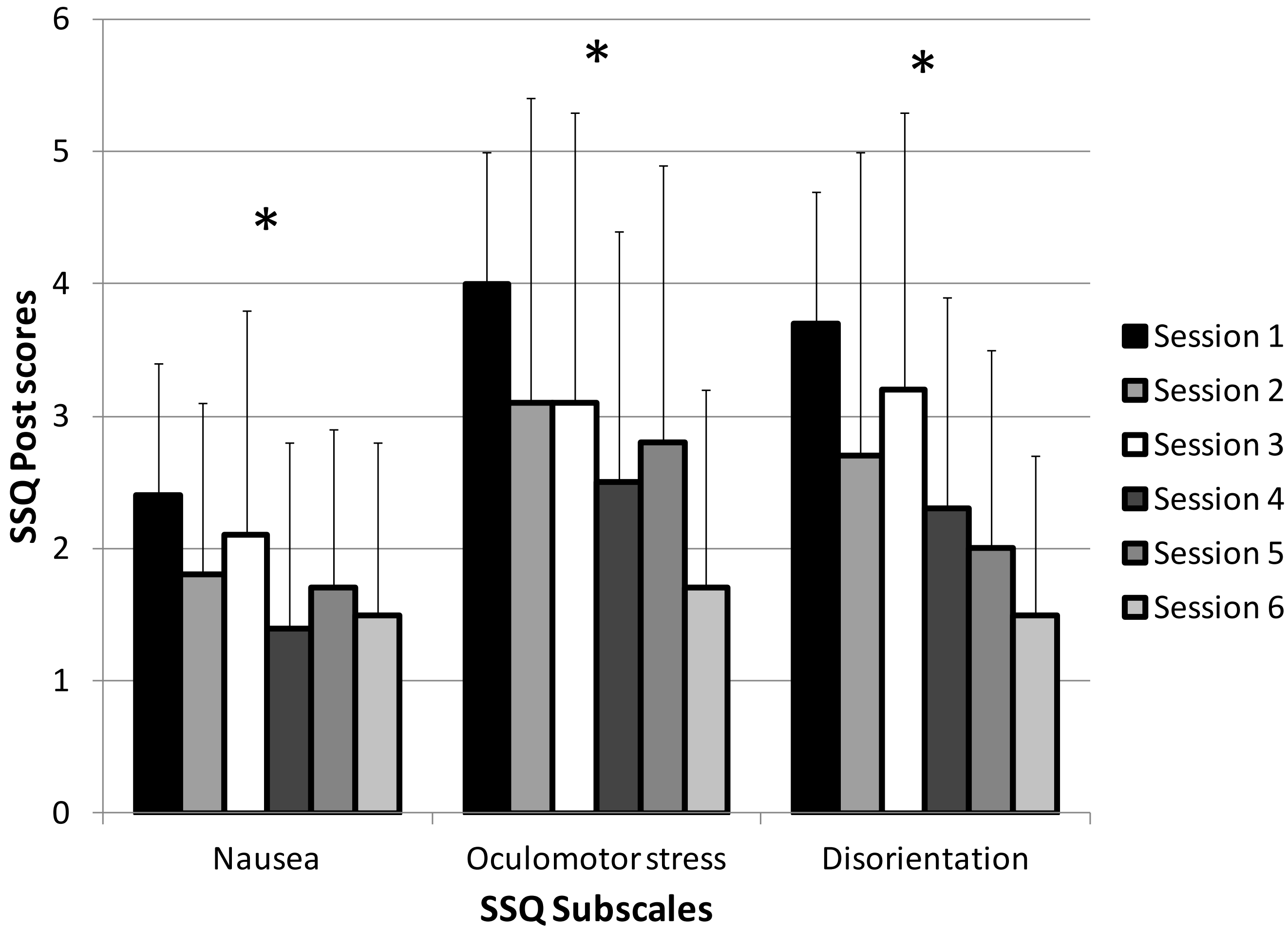

Figure 5-6: The Simulator Sickness Questionnaire (SSQ) post-treatment scores from session 1 to session 6. SSQ scores lessened significantly across treatment sessions. * The non-parametric Friedman test for magnitude of the post scores was significant ($p < 0.05$)

6.0 COMPARISON OF VIRTUAL REALITY BASED THERAPY WITH CUSTOMIZED PHYSICAL THERAPY FOR THE TREATMENT OF VESTIBULAR DISORDERS

6.1 INTRODUCTION

Individuals with vestibular disorders usually complain of dizziness, vertigo, balance problems, and falls.[1] Dizziness is one of the most common complaints to physicians in the United States responsible for over 8 million medical visits per year.[47] Hannford et al. (2005) reported that 20 % to 30 % of the general population have complaints of dizziness.[26] Among 546 falls of unknown origin presenting to the emergency room, 80% had symptoms of vestibular disorders and 40 % were complaining of vertigo.[10]

In individuals with vestibular disorders, information from the vestibular system is unreliable and individuals can become more dependent on information from non-vestibular inputs, particularly vision.[49, 104] Individuals may have space and motion sensitivity or discomfort in conditions and environments that may cause conflict among the somatosensory, visual, and vestibular systems.[2, 48] For example, individuals may report increased symptoms such as space phobia, supermarket syndrome, height vertigo, and visual vertigo in visually complex environments.[2, 4, 5, 81] Individuals report symptoms of disorientation, dizziness, and vertigo in moving visual environments associated with activities such as walking in crowded places while trying to recognize faces, walking in busy environments such as supermarkets while trying to find products, and driving in traffic while trying to recognize signs.[81] Visual vertigo is triggered by visual stimuli in specific visual environments and the individual often experiences dizziness.[81] A reduction of vestibular function in the challenging environment may lead to a mismatch among the sensory control systems.[49] Space and motion sensitivity can be displayed as increased body sway in challenging conditions that cause conflict among sensory control channels.[77, 78, 83, 321] Consequences of symptoms resulting from conflict among sensory control systems in challenging conditions may become critical and affect quality of life and participation in daily life activities when the individual develops avoiding behaviors.[48]

Vestibular rehabilitation is considered an accepted intervention for individuals with vestibular disorders.[1, 66, 88, 90, 92, 96, 274] Customized vestibular rehabilitation programs consist of exercises to encourage sensory compensation, vestibulo-spinal and vestibular ocular reflex (VOR) adaptation.[88] Vestibular rehabilitation has a positive influence on symptoms and impairments associated with vestibular disorders including 1) improving quality of life,[29, 86] 2) reducing vertigo and dizziness symptoms,[32, 42] 3) improving balance and physical functioning,[89] 4) reducing level of disability associated with dizziness,[34] 5) reducing anxiety symptoms,[94] and 6) reducing the risk of falls and improving postural control during standing and walking leading to improvements in self-care, occupational, and home management skills.[12, 29, 34, 44, 89-92, 94-97]

Part of the intervention for people with vestibular disorders is to practice visual-vestibular and/or somatosensory-vestibular alterations and manipulations.[11, 12] Sensory manipulation generally starts gradually with one sensory modality, then multiple alterations are advised. Visual information can be altered by asking subjects to perform exercises in busy environments or visually degraded environments.[11-13] The difficulty of the training can be increased gradually by adding vestibular stimulation such as incorporating head movements. Vestibular rehabilitation that includes repeated head movements with the exposure to visually complex environments aggravates dizziness with the intention of encouraging central tuning and recalibration.[65] Vestibular rehabilitation can be considered a form of behavioral intervention that teaches the individual to know the causes of dizziness and also to control and cope psychologically and systemically with the aggravating factors.[65-67]

Behavioral interventions including habituation exercises using virtual reality based therapy (VRBT) technology have been used to treat individuals with anxiety disorders such as fear of flying, panic disorder, social phobia, and post-traumatic stress disorders.[270, 322] Anxiety and psychiatric disorders are common among individuals with vestibular disorders; likewise, vestibular disorders are common among individuals with anxiety and psychiatric disorders.[49, 55] Individuals with both anxiety and vestibular disorders often describe dizziness as their chief complaint.[55] Dizziness and anxiety can exacerbate each other.[62] Consequently, the use of virtual reality based therapy for the treatment of vestibular disorders may provide an effective means of addressing both symptoms of dizziness and anxiety.

Habituation exercises have been used to treat individuals with vestibular disorders.[132] Visually provocative habituation exercises have been shown to be useful during vestibular rehabilitation.[14, 15, 163] Virtual reality based therapy is one emerging technology that can be used in vestibular rehabilitation to provide habituation exercises for individuals with vestibular disorders who become symptomatic in complex visual environments.[285, 305, 323] Virtual reality based therapy may be used to provide graded exercises in visually complex environments to train the brain to decrease the response to visual and vestibular stimuli.[285, 305] Using virtual reality based therapy in vestibular rehabilitation may be a successful way to facilitate desensitization of symptoms resulting from sensory conflict among visual, vestibular, and somatosensory systems. Provoking stimuli in the virtual world either through visual stimuli or visual-vestibular conflict may train the brain to correctly up-weight and down- weight sensory inputs for sensory control.[285, 305]

The purpose of this study is to examine if there is a difference in self report and performance measures between customized physical therapy and virtual reality based therapy in persons with vestibular disorders after a 6 week intervention program and at 6 months.

6.2 METHODS

6.2.1 Design

The protocol was approved by the University of Pittsburgh Institutional Review Board. A clinical trial was designed to compare virtual reality based therapy (VRBT) with the standard of care customized physical therapy (PT) in individuals with vestibular disorders, using a nonequivalent two-group pretest-posttest design.[324] For the PT intervention, subjects were treated for 6 treatment sessions (one session per week) by a physical therapist. For the VRBT intervention, subjects were treated for 6 treatment sessions (one session per week) using a virtual grocery store displayed in an immersive CAVE-like environment. Both interventions also included prescription of home exercises.

6.2.2 Subjects

The Tstudy consisted of 38 subjects with peripheral, central, or mixed vestibular disorders. Inclusion criteria were complaints of dizziness, imbalance, and abnormal objective laboratory testing (caloric testing, rotational chair testing, vestibular evoked myogenic testing, spontaneous nystagmus, and/or posturography). Exclusion criteria included the following: a history of neurologic disease, use of assistive devices for ambulation, a total hip or knee replacement, and severe arthritis. Subjects were recruited from the vestibular disorders clinic at the University of Pittsburgh after examination by a neurotologist. All subjects provided informed consent and agreed to participate in the study. The benefits and risks of the study were explained to participants during the recruitment period. The allocation of the subjects to the two intervention groups occurred in blocks of approximately 10 subjects over a four year period.

6.2.3 Intervention

6.2.3.1 Customized Physical Therapy (PT)

Subjects had six treatment sessions over the course of 6 weeks, a frequency that has been shown to improve outcomes in individuals with vestibular disorders.[90-93] An initial evaluation of 1 hour duration was followed by five (check) follow-up sessions lasting 45-60 min. (Describe the initial evaluation) Based on impairments and functional limitations discovered during the initial evaluation, the PT program was designed to address: 1) gaze stability in activities that require head movements such as shopping or walking in busy places; 2) space and motion sensitivity, 3) dizziness associated with head movements; and 4) postural instability and disequilibrium. Subjects were provided with home exercises for their dizziness and balance and were asked to maintain a daily exercise diary. Two physical therapists specialized in vestibular rehabilitation (the first therapist is a DPT, NCS with 20 years experience, 10 years in vestibular rehabilitation; the second therapist is a DPT with 8 years experience, 3 years in vestibular rehabilitation) performed the intervention.

6.2.3.2 Virtual reality based therapy (VRBT)

Subjects had six treatment sessions in the VRBT grocery store over the course of 6 weeks. The treatment session lasted for one hour and included six trials of habituation training; each trial was 4 minutes duration. The treatment session was conducted in the Medical Virtual reality based therapy Facility at the University of Pittsburgh (see details below). Two physical therapists administered the intervention (the first therapist is a DPT, NCS with 35 years experience as a PT, 27 years experience in vestibular rehabilitation; the second therapist is a PT with 12 years experience as a PT, 10 years in vestibular rehabilitation). Over the 6 week period, subjects were exposed to more visually complex aisles depending on the subject's tolerance. The therapists asked the subject to locate products on the shelves as they ambulated, and the subjects responded verbally when they located the product.

The subjects' tolerance to the virtual environments was assessed by recording their vital signs (blood pressure and pulse rate) and their Subjective Units of Discomfort (SUD, 0-100 range) before and after each trial.[258] The investigators used the SUDs score to determine if subjects should move to a more complex or less complex aisle in the VRBT. The session terminated if the SUD score indicated that the subject was highly symptomatic. Scores of 0 indicate no discomfort and scores of 100 indicate maximum discomfort. Subjects were given home exercises for their dizziness and balance and asked to keep a daily exercise diary.

6.2.3.3 Medical virtual reality based therapy center

The virtual environment consists of a grocery store modeled in 3D Studio Max and imported into Unreal Tournament (UT2004), adapted for multi-screen environments with the CaveUT modification.[304] The store scene is displayed on 3 screens that surround the subject in a full-field CAVE-like environment (Figure 5-1). The store contains 16 aisles (20 m long) and has

8 levels of visual complexity that depend on the spatial frequency and contrast of the product textures. The aisles increase in complexity from aisle one to aisle sixteen.

Three 2.4 X 1.8 m (vertical X horizontal) back-projected screens were used. The side screens make an included angle of 110º with the front screen. The front screen is 1.5 m from the user, and the opening of the structure at the location of the subject is approximately 2.9 m from the front screen. The images are displayed using Epson 810p PowerLite LCD monoscopic projectors, with a pixel resolution of 1024 X 768 for each screen. Each projector is connected to an NVIDIA GeForce4 graphics processing unit (64 MB texture memory) installed in a separate PC (Pentium, 2.2 GHz, 512 MB RAM) running Windows XP. The movement of the images on the three PCs is synchronized and controlled by a server via a local area network. The update rate of the images is consistently at least 30 frames per second.

The virtual environment is interfaced to a custom-built treadmill, 2.0 m long and 1.2 m wide with a maximum velocity of 1.2 m/s. At the front end of the treadmill is a grocery cart that is instrumented with two load cells on the push bar. The velocity of the treadmill and movement within the environment is controlled by the force applied to the cart.[305] Turns in the virtual grocery store were made by pushing harder on one side of the push-bar compared to the other.

6.2.4 Outcome measures

Subjects were examined one week before, one week after, and 6 months after the intervention using self-report and performance-based measures of functional balance by a physical therapist blinded to treatment groups.

6.2.4.1 Self-report measures

The Activities-specific Balance Confidence scale (ABC) was used to record the individual's perceived level of balance confidence during 16 daily living activities.[240] Responses ranged from 0% to 100%; the lowest score indicated low confidence in balance and the highest score indicated high level of confidence.[240] The Dizziness Handicap Inventory (DHI) recorded the level of disability and handicap resulting from dizziness.[33] The DHI score ranged between 0% to 100% with the lowest score indicating low disability resulting from dizziness and the highest score indicating a high level of disability. The sum score of all DHI subscales was reported. For the Situational Characteristics Questionnaire (SCQ), subjects rated situations that elicited anxiety or discomfort for the subject in real life situations.[80] The SCQ (part A) score ranged between 0 and 30 with the highest scores (worse) on the SCQ-A indicate that persons have greater discomfort or anxiety performing normal activities such as shopping, riding in a car or bus, in movie theaters, on escalators or elevators, and in the shower. The SCQ (part A) has shown its ability to distinguish individuals with vestibular dysfunction among individuals complaining of anxiety disorders.[80, 246] The SCQ (part B) ranged between 0 and 60 with the highest scores (worse) on the SCQ-B indicate that persons have greater discomfort or anxiety associated with vestibular symptoms. The SCQ-B has shown its ability to identify people with vestibular disorders.[246]

6.2.4.2 Performance measures

The Dynamic Gait Index (DGI) examined a person's ability to perform various gait activities such as walking with head turns and avoiding obstacles.[247] The scale has 8 items; each item can be scored from 0 to 3 (0 means severe impairment, 3 means normal ability). The optimal score on the DGI is 24 and below 19 the subject has a high risk of falling.[248, 314] The

Functional Gait Assessment (FGA) measured balance control during walking.[250] The FGA has 10 walking tasks. The FGA total score is 30 with each item scored using an ordinal scale (0-3, 0 = severe impairment, 3 = normal performance). Scores of 22 or less have been related to fall risk in older adults.[252] To record gait speed, subjects walked 6.1 meters at their comfortable speed 5 times, with their mean speed calculated. Gait speed has shown to be related to falls and functional abilities.[254, 308] The Timed Up and Go (TUG) test required subjects to rise from a chair, walk three meters, turn around, then walk back to the chair and sit.[296] Subjects were timed during the task; persons with vestibular disorders who score 13.5 seconds or greater are at high risk of falling.[255] The Sensory Organization Test (SOT) was used to record postural sway in six conditions related to various sensory inputs important for balance (vestibular, vision, and somatosensory input).[192] The composite SOT score was used in the analysis.

6.2.5 Statistical analysis

A 2 × 3 mixed analysis of variance was performed on self-report and performance measures as a function of time and intervention type. The within-subjects independent variable was assessment time with 3 levels (pre, post, and 6-month follow up). The between subjects independent variable was the intervention type with 2 levels (VRBT, PT). The Greenhouse-Geisser correction was applied in all cases. Post-hoc testing was performed using a Bonferroni correction with 3 planned comparisons (pre vs. post, pre vs. 6-month follow up, and post vs. 6-month follow up) and $\alpha = 0.017$. Intention to treat analysis was used for subjects with missing data at the 6 months follow up (4 subjects did not return in VRBT group, 2 subjects did not return in PT group). The assumption of normality was met for all self-report and performance measures except for the DGI and SOT. For the measures that were not normally distributed, the Mann-Whitney U test was used to compare intervention groups at each assessment time, and the Wilcoxon signed ranks test was used to test for the significant differences between assessment times (average of both intervention groups).

6.3 RESULTS

6.3.1 Participants

The demographic information of all subjects including age, gender, duration of symptoms, and laboratory tests for individuals [oculomotor testing, positional testing, calorics testing, rotational chair testing, and vestibular-evoked myogenic potentials (VEMPs)] are presented in Table 10 for both groups. There were no significant differences between groups in demographic characteristics, laboratory tests, location of dysfunction, and duration of symptoms.

6.3.2 Self-report and performance measures

Table 11 provides the differences between study groups in all self-report and performance measures at baseline. There were no significant differences between two groups in all self-report and performance measures at baseline ($p > 0.05$). A t-test was also used to compare groups at end of therapy and at 6-moth follow up. There was no significant differences between the two groups in all self-report and performance measures ($p > 0.05$) at either time point. For the DGI and SOT, Mann-Whitney U test was used to compare groups at end of therapy and at 6-month follow up. There was no significant differences between the two groups ($p > 0.05$) at either time point for the DGI, there was a significant difference between the two groups ($p = 0.03$) only at end of therapy for the SOT.

There were no significant differences on self-report and performance measures between intervention types averaged across assessment times, $p > .05$. There was a significant difference on self-report and performance measures due to time, averaged across intervention types, $p < .05$, effect size eta-squared (η^2) range (.1 - .4), Table 12.

In order to determine the pattern of differences on the self-report and performance measures depending on assessment time, post hoc pairwise comparisons were performed using the Bonferroni adjustment. Table 13 shows significant improvement in all self-report measures, except SCQ-A, after the intervention ($p < .001$). At the 6-month follow up, subjects maintained their improvement in these self-report measures, $p < .001$. For the performance measures, significant improvements were observed on gait speed ($p = .02$), but not for the FGA and TUG (Table 14). For all self-report and performance measures, there was no significant differences between post and 6-month follow up.

For the measures that were not normally distributed (DGI, SOT), the Mann-Whitney U test was used to compare intervention groups at each assessment times, there were no significant differences on DGI and SOT between intervention types, $p > .05$. The Wilcoxon signed ranks test was used to test for the significant differences among assessment times on DGI and SOT; significant improvements were observed on the DGI ($p = .001$) and the SOT ($p = .002$) average score, and subjects preserved their recovery on the DGI and SOT at the 6 month follow up (Table 15).

6.4 DISCUSSION

In this study we examined the difference in self report and performance measures between customized physical therapy and virtual reality based therapy in persons with vestibular disorders. Groups were similar at baseline in all self-report and performance measures. Both groups improved significantly in 3 of the 4 self-report measures, in 3 of the 5 performance measures, and maintained these improvements 6 months after the intervention ended. Our study findings suggest that using VRBT in vestibular rehabilitation produces equivalent outcomes for individuals with vestibular disorders when compared with the clinically accepted physical therapy.

The feedback from the cart provided important information to the patient related to direction of navigation and speed inside the virtual environment which may have enhanced the level of immersion and the feeling of presence inside the environment, but may not necessarily improved gait speed. Subjects in the customized physical therapy group received different gait exercises which may have improved gait speed compared with the VRBT group. The minimal clinical important difference for gait speed is 0.1 m/s, the number of subjects who improved by a clinically significant amount is higher in the customized physical therapy group (8 subjects) compared to the VRBT group (4 subjects). Physical therapists in the customized physical therapy group may have had more chances to modify the difficulty of the training and to customize exercises every session based upon the patients' conversations within the session. In the VRBT, difficulty of the training was based on the patient's level of discomfort (0-100) and the physical therapist only controlled the amount of visual stimuli from the easy aisle to a more complex aisle (1 to 16).

The current study extends the work of previous studies that examined the use of technology-based visual stimuli for vestibular rehabilitation. Previous studies delivered optokinetic stimulation in horizontal and vertical directions to individuals who had unilateral and bilateral vestibular disease.[14, 82] The subjects were no longer symptomatic after an average of 8 sessions lasting 15 minutes, and subjects increased VOR gain, and posturography scores were improved.[14, 82] Suarez et al (2006) reported on using head mounted display that provides optokinetic stimulation, and visuo-vestibular interaction in older subjects with balance disorders. At the end of the six-week, daily intervention subjects demonstrated reduced sway.[317] Several notable differences exist between the previous studies and the current study. The VRBT was designed to increase subject interaction with the grocery store environment in which individuals commonly report increased symptoms rather than just relying on optokinetic stimulation. Also, subjects performed a functional task within the environment, by walking and moving their head to search for products that they would encounter in a real grocery store. In vestibular rehabilitation, individuals are encouraged to move their head during daily activities because movement is needed for adaptation and reweighting of the sensory signals.[319, 320]

Vestibular rehabilitation using the VRBT included repeated head movements with the exposure to visually complex environments that aggravate vestibular symptoms. Vestibular symptoms aggravated mostly by head, body, or the surrounding motion is considered dynamic vestibular imbalance.[106] Using VRBT, visual information is critical for recovery from the dynamic vestibular imbalance. Vestibular ocular reflex gain does not improve without visual inputs.[106]

The mechanism of habituation can explain the success of vestibular rehabilitation for individuals in the VRBT and customized physical therapy groups. During habituation, graded exercises are used to train the brain and to decrease the response to the visual, vestibular, and somatosensory stimuli, and to facilitate desensitization of symptoms resulting from sensory conflict among visual, vestibular, and somatosensory systems. The central nervous system is trained to correctly up-weight and down-weight sensory inputs to improve postural control.[132] Short term compensation occurs after a lesion in the vestibular system and leads to reductions of symptoms like nausea, unsteadiness, and motion sensitivity. Chronic dizziness occurs when short term compensation is disrupted because of the severity of the lesion or impairment in the CNS.[1, 95, 133]

Vestibular rehabilitation in both groups provided long term improvements for vestibular disorders. Vestibular adaptation exercises to the VOR during the movement of the image on the retina combining head movement and visual inputs to the CNS can cause long term VOR adaptation.[142-147] Vestibular habituation to provoking stimuli also leads to long term improvement.[15] The provoking stimuli of either visual or visual-vestibular conflict are repeated at regular intervals aiming to raise the threshold at which symptoms are aggravated. The general role for vestibular habituation to such stimuli, in both the VRBT and the PT groups, is that stimuli are provided slowly and the increases in the intensity of the stimuli should be according to the individual's tolerance.[11, 273]

Pavlou et al. (2004) studied 2 groups of subjects with chronic unilateral vestibular disorders; one group received customized physical therapy and the other group received customized physical therapy in combination with exposure to moving visual displays.[15] Both groups demonstrated significant improvements over the course of 8 weeks (16 visits), but subjects who received the additional visual-based treatment had greater improvements, in particular with space and motion discomfort. The combination of PT and VRBT in Pavlou study may explain the differences in the findings.[15] In our study, subjects in the VRBT group did not receive customized physical therapy. The combination of both VRBT and PT may provide better results than just PT or VRBT alone. Dosage of intervention was different in both studies with one session/ week for 6 weeks in our study and 2 session/ week for 8 weeks in Pavlou et al study. Subject criteria were different in both studies. Pavlou et al included only subjects with peripheral vestibular loss (homogenous sample) and our study included subjects with peripheral, central, and mixed vestibular disorders (heterogeneous sample). Secondary analysis also compared subjects with high space and motion sensitivity reported in SCQ at baseline in both groups, no significant differences were found between study groups.

Vestibular rehabilitation using the VRBT considers that the vestibular system is context-specific plastic and the adaptation of the VOR depends on the frequency, direction, and environment of habituation.[142-147] The success of vestibular habituation using VRBT depends on providing the appropriate error signal that drives vestibular adaptation. The error signals using the VRBT were provided through visual stimulation and visual flow signals to the CNS.[15, 82] Successful vestibular rehabilitation evaluates the sensory weighting for orientation in space and addresses performing exercises in altered visual/ somatosensory/ vestibular environments.[90, 148] The brain has the ability to weight and reweight the person's reliance on sensory modalities for orientation and postural control.[149] Virtual reality based therapy (VRBT) is one emerging technology that can be used in vestibular rehabilitation that may help individuals with vestibular disorders to lessen hypersensitivity to visual and motion stimuli, reduce the avoidance of activities, and progress self-confidence.[15] However, currently the cost and effort of using VRBT is high compared to PT, so there is no advantage of using VRBT since the results were similar between the VRBT and PT groups.

6.4.1 Limitations and future work

This is a nonrandomized study, by including a heterogeneous sample in the efficacy study, it may have influenced the results. However, examination of the type of dysfunction (peripheral, central or mixed) did not reveal any strong relationship between the magnitude of improvement and site of dysfunction, therefore, we are unable to state a relative benefit in any one type of diagnostic category. Subjects in the VRBT group did not receive customized physical therapy in the clinic, future research should consider the combination of both the VRBT and PT interventions and compare the three groups (VRBT group, PT group, and VRBT + PT group).

6.4.2 Conclusion

The use of virtual reality based therapy appears to improve symptoms for individuals with vestibular disorders at least as much as customized physical therapy. The VRBT can be used as a habituation technique for individuals with vestibular and balance disorders and provides similar effects to customized physical therapy; therefore, the VRBT may be used as a tool in vestibular rehabilitation. However, currently the cost and effort of using VRBT is high compared to PT, so there is no advantage of using VRBT since the results were the similar between the VRBT and PT groups.

Table 10: Characteristics and demographics of subjects in the virtual reality based therapy group (VRBT) and the customized physical therapy group (PT) at baseline concerning age, gender, duration of symptoms, laboratory tests, location and side of dysfunction (n = 38)

	VRBT group	PT group	P
Age (years)			
Mean ± SD	53.7 ± 9	59.8 ± 13	.57
Range	27 – 70	30 - 78	
Gender			
Female	15	16	.28
Male	5	2	
Duration of symptoms (months)			
Mean ± SD	5 ± 4	7 ± 5	.4
Median	4.5	5.5	
Range	1-16	.25-21	
Abnormal laboratory testing (n)			
Oculomotor	2	0	.16
Positional	6	9	.22
Calorics (reduced vestibular response)	6	9	.35
Rotational Chair (decreased gain, asymmetry)	10	5	.17
VEMPs	7	9	.12
Location of dysfunction			
Peripheral	12	12	.94
Central	3	2	
Mixed	4	3	
Unknown	1	1	
Side			.67
Right	7	9	
Left	7	0	
Bilateral	1	2	
Unable to determine side of lesion	2	5	

VEMP: vestibular-evoked myogenic potentials.

Table 11: Self-report and performance measures (mean ± SD) for subjects in the virtual reality based therapy (VRBT) and the customized physical therapy groups (PT) at baseline

Outcome measures	Pre (VRBT)	Pre (PT)	p value t-test
ABC	66 ± 20	67 ± 30	.91
DHI	38 ± 17	37 ± 26	.91
SCQ part A	4 ± 3	4 ± 3	.87
SCQ part B	20 ± 13	20 ± 14	.98
FGA	24 ± 7	21 ± 7	.10
DGI	21 ± 2	19 ± 5	.16
Gait speed	1.13 ± .2	1.10 ± .2	.25
TUG	9 ± 1.6	10.5 ± 3.6	.10
SOT	63 ± 18	55 ± 20	.20

Higher scores on the Activities-specific Balance Confidence scale (ABC), Functional Gait Assessment (FGA), Dynamic Gait Index (DGI), gait speed, and Sensory Organization Test (SOT) indicate better outcomes at baseline. Lower scores on the Dizziness Handicap Inventory (DHI), Timed Up and Go (TUG), and Situational Characteristics Questionnaire (SCQ) indicate better outcomes at baseline.

Table 12: Using repeated ANOVA, the pattern of difference on self-report and performance measures among assessment times (interaction effect); group effect with 2 levels (VRBT, customized physical therapy); assessment time effect with 3 levels (pre, post, 6 month follow up)

Outcome measures		Group	Assessment time	Group x Assessment time
Self-report measures:				
ABC	p value	0.92	**.000**	.42
DHI		0.75	**.000**	.90
SCQ-A		0.60	.33	.39
SCQ-B		0.83	**.000**	.77
Performance measures:				
FGA	P value	0.11	**.048**	.48
Gait speed		0.60	**.007**	.25
TUG		0.82	.15	.08

Higher scores on the Activities-specific Balance Confidence scale (ABC), Functional Gait Assessment (FGA), and gait speed indicate better outcomes. Lower scores on the Dizziness Handicap Inventory (DHI), Timed Up and Go (TUG), and Situational Characteristics Questionnaire (SCQ) indicate better outcomes.

Table 13: Self-report measures (mean ± SD) for subjects in the virtual reality based therapy group (VRBT) and the customized physical therapy group (PT) at pre-treatment vs. post-treatment vs. 6-month follow-up with the effect size (ES), (n=38)

Outcome measures	Group	Pre	Post	6-month Follow-up	p value (Pre v. Post)	p value (Pre v. 6-months)	P value (Post v. 6-month)	ES
Self-report measures								
ABC	VRBT	66 ± 20	75 ± 20	81 ± 16				
	PT	67 ± 30	79 ± 28	78 ± 29				
	Total	66 ± 25	77 ± 24	80 ± 23	**.000**	**.000**	.24	.33
DHI	VRBT	38 ± 17	26 ± 19	25 ± 17				
	PT	37 ± 26	23 ± 23	22 ± 22				
	Total	37 ± 21	25 ± 21	24 ± 19	**.000**	**.000**	.95	.3
SCQ part A	VRBT	4 ± 3	3 ± 2	4 ± 3				
	PT	4 ± 3	3 ± 3	3 ± 3				
	Total	4 ± 3	3 ± 2	3 ± 3	.65	.60	.98	.05
SCQ part B	VRBT	20 ± 13	13 ± 10	13 ± 10				
	PT	20 ± 14	14 ± 15	14 ± 15				
	Total	20 ± 13	14 ± 12	14 ± 12	**.000**	**.001**	.86	.3

Higher scores on the Activities-specific Balance Confidence scale (ABC) indicate better outcomes. Lower scores on the Dizziness Handicap Inventory (DHI) and Situational Characteristics Questionnaire (SCQ) indicate better outcomes.

Table 14: Performance measures (mean ± SD) for subjects in the virtual reality based therapy group (VRBT) and the customized physical therapy group (PT) for pre-treatment vs. post-treatment vs. 6-month follow-up, with the effect size (ES), (n=38)

Outcome Measures	Group	Pre	Post	6 month Follow-up	p value (Pre v. Post)	p value (Pre v. 6-month)	p value (post v. 6-month)	ES
Performance measures								
FGA	VRBT	24 ± 7	25 ± 3	25 ± 4				
	PT	21 ± 7	24 ± 6	23 ± 7				
	Total	22 ± 7	24 ± 5	24 ± 6	.07	.27	.94	.1
Gait speed	VRBT	1.13 ± .2	1.14 ± .1	1.12 ± .1				
	PT	1.10 ± .2	1.15 ± .3	1.10 ± .2				
	Total	1.10 ± .2	1.15 ± .2	1.11 ± .2	**.02**	.40	.11	.1
TUG	VRBT	9 ± 1.6	9.2 ± 1.3	9.3 ± 1.5				
	PT	10.5 ± 3.6	9.5 ± 3.5	9.9 ± 3.2				
	Total	9.7 ± 2.8	9.3 ± 2.6	9.6 ± 2.4	.20	.93	.19	.06

Higher scores on the Functional Gait Assessment (FGA), Dynamic Gait Index (DGI), gait speed, and Sensory Organization Test (SOT) indicate better outcomes. Lower scores on the Timed Up and Go (TUG) indicate better outcomes.

Table 15: Non-parametric statistics for Dynamic Gait Index (DGI) and Sensory Organization Test (SOT), mean ± SD, for subjects in the virtual reality based therapy group (VRBT) and the customized physical therapy group (PT) for pre-treatment vs. post-treatment vs. 6-month follow up

Outcome measures	Group	pre	post	6 month Follow-up	p value (Pre v. Post)	p value (Pre v. 6-month)	p value (post v. 6-month)
DGI	VRBT	21 ± 2	22 ± 2	22 ± 2			
	PT	19 ± 5	21 ± 4	20 ± 6			
	Total	20 ± 4	21 ± 3	21 ± 4	**.001**	**.001**	.52
SOT	VRBT	63 ± 18	68 ± 19	69 ± 17			
	PT	55 ± 20	57 ± 24	62 ± 20			
	Total	60 ± 19	62 ± 22	66 ± 19	**.002**	**.000**	.29

7.0 RELIABILITY AND VALIDITY OF THE BALANCE REHABILITATION UNIT ASSESSMENT MODULE

7.1 INTRODUCTION

Falling is a risk factor associated with vestibular disorders that can impact quality of life (QoL) and reduce participation in daily life activities including physical and psychological aspects.[29, 31] Vestibular disorders may be the main intrinsic factor leading to incidents of falling among the elderly; among 546 incidents of falling that resulted in a visit to an emergency department, 80 % had vestibular impairments and 40 % were complaining of vertigo.[10] The incidence of falls among individuals with bilateral vestibular loss (51%) is significantly higher than the incidence of falls in the general population (25%) in people between 30-80 years of age.[29]

Aging is an important factor that influences postural control.[22, 25, 222-226, 325-332] Falls rates among elderly people are at least 42% per year, and considered the seventh most frequent cause of death in people over 60.[23, 333] The American and British Geriatric Society and American Academy of Orthopedic Surgery guidelines for prevention of falls in the elderly have described many risk factors for falls associated with aging including: decreased sensory function, visual problems, vestibular problems, use of assistive devices, and history of falls.[25, 84, 85, 213]

Measuring sensory control during standing may help to investigate age and vestibular disease effect on balance.[25, 227, 228] Quiet stance is typically associated with small amounts of sway that assist the body in maintaining equilibrium.[18, 19] Center of pressure (COP) sway magnitude is dependent on the following conditions: 1) exposure to accurate, inaccurate or absent visual information [190, 191, 194], 2) exposure to different support surfaces that provide accurate, inaccurate, or absent somatosensory information [3, 186, 187, 195, 197], and 3) intact or disrupted vestibular sensation.[20, 198, 207, 233, 334] According to the sensory weighting model of postural control, sensory information for balance and orientation are not weighted independently, and the CNS takes into account the task/environment characteristics for orientation and postural control.[190] The CNS has the ability to resolve sensory conflict among visual, vestibular, and somatosensory systems that may happen in altered sensory environments.

Nashner et al. studied sensory organization and body sway in six different conditions that investigated the effect of presence/absence and accurate/inaccurate sensory information from vision, somatosensation, and vestibular systems.[297] Condition 1 examined how the 3 systems (vision, vestibular, and somatosensory) contributed to balance control. Conditions 2 and 3 examined how absent or inaccurate visual feedback information may influence balance control. Condition 4 examined how inaccurate somatosensory information influences balance. Conditions 5 and 6 examined how inaccurate somatosensory plus the absence or inaccuracy of visual feedback may influence postural control.[189] Interrupting sensory information from the legs among healthy individuals increased COP sway. Intact vestibular information assists subjects to maintain balance when somatosensory or visual information are disrupted. When tested during conditions 5 and 6, where information from both vision and somatosensory is reduced or made inaccurate, individuals with vestibular disorders, had increased COP sway and experienced sudden falls.[232]

Measuring postural control during standing has been investigated using low and high tech methods. Shumway-Cook and Horak (1986) described the use of a sensory conflict dome and foam to provide visual sway referenced and inaccurate somatosensory feedback. The foam provides destabilization in conditions 4, 5, and 6; the dome provides visual vestibular conflict in conditions 3 and 6. Sway is observed and subjectively quantified on a scale 1 to 4 (1= minimal sway, 2= mild sway, 3= moderate sway, 4= fall).[199] The study suggested that the test can assist clinicians to identify patterns of instability, and that the test does not provide a comprehensive approach to balance assessment.

Methods of quantifying sway have been developed using computerized dynamic posturography such as the Equitest (Neurocom, Inc). The Sensory Organization Test of the Equitest is used to measure postural control under various standing conditions. The SOT utilizes a tilting floor and moving walls to provide inaccurate somatosensory and visual sway referenced feedback during standing. Tilting of the floor provides sensory destabilization in the sagittal plane resulting in measured COP sway in the antero-posterior (AP) direction. The movement of the walls is also in the sagittal plane. However, studies show that difficulty controlling balance in the mediolateral (ML) direction is associated with the history of falls, and can be predictive of falls in the future among elderly people.[335, 336]

The difference between the use of foam versus use of tilting floor to provide inaccurate somatosensory feedback has been studied. Allum et al (2002) compared the amount of sway associated with standing on foam with eyes open and closed, with standing on a platform tilting in the AP or mediolateral ML direction with eyes open and closed. During platform AP sway-referencing, sway velocity in the ML direction was reduced in the 2 - 5 Hz range compared with the platform ML sway-referencing and the foam. Sway velocity in the AP direction increased up to 1 Hz compared with the foam. During the platform ML sway-referencing, ML sway velocity was similar to ML sway velocity on the foam but higher than sway velocity on the platform AP sway-referencing. The study concluded that 1) the use of the foam is a more complex balance task than the platform AP sway-referencing, and 2) while standing on foam, subjects must coordinate ML and AP sway simultaneously.[201]

The recently developed Balance Rehabilitation Unit (BRU, Medicaa Balance for life, Interacoustics) utilizes a head mounted display and foam as part of the sensory organization assessment SOT.[317, 337-339] However, the psychometric properties of the BRU need to be established. The aims of this study include: 1) to examine the test-retest reliability of the BRU in young healthy, older healthy, and individuals with vestibular disorders, 2) to examine the concurrent validity of the BRU compared to the SOT, and 3) to examine age and disease effects on balance performance using the BRU (discriminative validity).

7.2 METHODS

7.2.1 Design

The study is an experimental-cross sectional design. Each subject was tested twice on the BRU and one time on the SOT during the same visit. Subjects were given a 15 minute break after each test on the BRU and SOT. To minimize the "order effect" bias, the order of testing of the two devices was changed with every other subject. For both devices, every subject was tested in 6 conditions and had 3 trials per condition, with 20 second trials.

7.2.2 Subjects

The study included 90 subjects; 30 subjects with vestibular disorders between the age of 18 to 85 who were referred by a neurotologist; 30 young healthy controls between the age of 18 and 50; and 30 older healthy controls between the age of 60 and 85. A power analysis based on finding differences in sway between young and older healthy adult subjects was conducted to determine the appropriate number of subjects to be tested. An estimate of the number of subjects required to attain a power of 0.8 with alpha = 0.05 was 30 in each group.

Exclusion criteria for all subjects included known pregnancy and the use of assistive devices for standing. For the healthy control subjects, exclusion criteria included symptoms of inner ear disorders such as complaints of dizziness, vertigo, or balance problems. Healthy controls were screened before testing to confirm that subjects did not have vestibular disorders. Exclusion criteria for controls included the following: 1) observation of spontaneous nystagmus, 2) abnormal oculomotor assessment, 3) positive Dix-Hallpike or roll test for benign paroxysmal positional vertigo, 4) positive horizontal head shake test and head thrust test for vestibule-ocular reflex dysfunction. The study protocol had been approved by the University of Pittsburgh Institutional Review Board, and all subjects provided informed consent and agreed to participate in the study.

Healthy subjects were recruited through local advertisements and from previous balance research studies. Individuals with vestibular disorders who had complaints of dizziness, vertigo, balance problems, falls, or difficulty focusing were recruited from the practice of a neurotologist. Vestibular disorder diagnosis and vestibular laboratory test results (audiogram, oculomotor testing, positional testing, calorics testing, rotational chair testing, and vestibular evoked myogenic potentials) were retrieved from the individuals' medical records. Figure 7-1 is a participant flow diagram that includes information about number of subjects recruited, excluded/included in each group, tested, and included in the analysis.

The demographic and clinical information of all subjects including age, gender, duration of symptoms, and laboratory tests for individuals [oculomotor testing, positional testing, calorics testing, rotational chair testing, and vestibular-evoked myogenic potentials (VEMPs)] are presented in Table 16.

7.2.3 Assessment devices

The BRU consists of a force platform, a head mounted display (HMD) device that displays different visual environments, overhead safety harness, and foam cushion. The BRU measures COP sway area (SA) and COP sway velocity (SV) under 6 different testing conditions that assess the same sensory organization abilities as the SOT and CTSIB, including: Condition 1: standing on a firm surface eyes open looking forward, Condition 2: standing on a firm surface with eyes closed, Condition 3: standing on a firm surface viewing a stationary visual scene (basketball gym) displayed in the HMD, Condition 4: standing on foam eyes open looking forward to a wall, Condition 5: standing on foam with eyes closed, and Condition 6: standing on foam viewing a stationary visual scene displayed in the HMD. In a similar fashion to the SOT conditions, in conditions 3 and 6 the head fixed visual environment moves with the subject, and thus provide sway referencing. In conditions 4, 5, and 6, the form surface distorts the normal reference to ground sensed by lower extremity somatosensation.

The Smart Equitest (Neurocom, Inc) consists of a movable platform that is surrounded on three sides by panels that sway with the subject (i.e sway-referenced visual surround). Testing conditions included: 1) standing on a firm surface eyes open looking forward, 2) standing on a firm surface with eyes closed, 3) standing on a firm surface with a sway-referenced visual surround, 4) standing on a sway-referenced platform that pivots about the ankles with eyes open, 5) standing on a sway-referenced platform with eyes closed, and 6) standing on a sway-referenced platform and sway-referenced visual surround.

7.2.4 Outcome measures

A common balance variable that has been used in many studies of balance is the center of pressure (COP). The COP represents the center of distribution of the total force of body weight on the ground and is considered an active variable that moves continuously. It is computed from data points distribution and recorded in the anteroposterior (A/P) and mediolateral (M/L) directions at a sampling frequency of 50 Hz.[171, 340] The COP A/P and COP M/L were used to estimate sway area (SA), sway velocity (SV), root mean square RMS (A/P, M/L) and peak to peak PTP (A/P, M/L). The measures of SA and SV are the normal output of the BRU; the measures of RMS and PTP were also calculated of their use in many studies.

Sway area was measured in cm^2. The standard method to estimate this area is by computing a 95 % confidence ellipse of the distribution of COP coordinates in the A/P and M/L directions. The statistical definition of this ellipse is that there is 95% confidence that the center of a population would be inside the ellipse and that SA is the estimation of the area of the ellipse. The following standard formula was used to calculate SA:

$$Area = 2 * \pi * F_{0.05[2,n-2]} * \sqrt{\sigma_{ap}^2 \sigma_{ml}^2 - \sigma_{ap.ml}^2}$$

F is the Fisher distribution at 95%, σ^2_{ap} is the variance of COP data in the APdirection, and σ^2_{ml} is the variance of COP data in the ML direction, $\sigma^2_{ap.ml}$ is the covariance of COP data in the AP and ML directions, (2, n-2: degrees of freedom); For the sample of 1000 data points (20 s * 50 Hz), F was equal to 3.

Sway Velocity (SV) was computed using the following:

$$Dxy = \sum_{i=1}^{n-1} \sqrt{\left(COPap_{i+1} - COPap_i\right)^2 + \left(COPml_{i+1} - COPml_i\right)^2}$$

$$SV = Dxy / T$$

T is the duration of the trial, SV is sway velocity, Dxy is path length, COPap is the data distribution in the AP direction, and COP ml is the data distribution in the ML direction. A Butterworth low pass filter (4^{th} order, 2Hz cutoff) was used in Matlab to calculate filtered sway velocity (FSV) to reduce noise.

Root mean square (RMS) was computed using the following:

$$RMSap = \sqrt{\frac{\sum_{i=1}^{n} COPapi^2}{n}} \qquad RMSml = \sqrt{\frac{\sum_{i=1}^{n} COPmli^2}{n}}$$

Peak to Peak (PTP) was calculated using the following:

$$PTPap = \max\,(COPap) - \min\,(COPap)$$

$$PTPml = \max\,(COPml) - \min\,(COPml)$$

Max (COPap) is the highest sway amplitude in the AP direction, Min (COPap) is the lowest sway amplitude in the AP direction, Max (COPml) is the highest sway amplitude in the ML direction, and Min (COPml) is the lowest sway amplitude in the ML direction.

7.2.5 Statistical analysis

To investigate the test-retest reliability, the intra-class correlation coefficient (ICC) was used for the entire group of 90 subjects and within each study group; the ICC considers both correlation and agreement and provides a single index to describe reliability. The ICC uses variance estimates from the analysis of variance (ANOVA), and it can assess the reliability among more than 2 readings. The ICC considers the differences between observed scores that are due to variations of the measurement system including factors related to the testing environment and subject conditions. The interpretation includes the following: ICC >.75 indicates excellent reliability, .40-.74 indicates fair to good reliability, and <.40 indicates poor reliability.[341]

The purpose and design of this study involved the use of the same rater representing the only raters of interest, with no intention of generalizing findings beyond the raters involved. The rater was considered a fixed factor and not randomly selected in this design. The average of 3 trials/ condition was used. The intra-class correlation coefficient, ICC (3, 1) and 95% CI were used to describe the level of agreement between test and retest.

For absolute reliability, the average mean difference between trials with confidence limits, the standard error of measurment (SEM), and the Bland and Altman method were used to describe the extent to which a balance score varies on test-retest measurements.[263-268]

Secondary analysis included evaluation of standard error of measurment proportion (SEM %), minimal detectable change (MDC_{95}), and minimal detectable change proportion (MDC %), and were calculated using these following formulas:

$$SEM = sd \times \sqrt{(1 - \mathrm{r})} \qquad SEM\ \% = \frac{SEM}{MEAN} \times 100$$

$$MDC_{95} = \mathrm{SEM} \times 1.96 \times \sqrt{2} \qquad MDC\ \% = \frac{MDC95}{MEAN} \times 100$$

The SEM can be interpreted as the standard deviation of measurement errors, and the smaller the SEM, the smaller the deviation of measurement errors around the true mean and the more reliable the measure.[342] The SEM% also provides information about measurement error, and the smaller the SEM% means lower measurement error. The MDC_{95} is a clinically useful measure for absolute reliability and estimates the true change versus the error change.[342] It indicates how much change must occur in a measure with a given degree of random error (the SEM), and with 95% certainty, to conclude that change is due to true change not error change. The MDC% provides information about measurement responsiveness, and the smaller the MDC% the higher the responsiveness. It provides insights about what is the percentage of the mean the subject needs to score to be considered a clinical change.

To examine the concurrent validity of the BRU in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders, Spearman rank order correlation (*rho*) between the BRU (time 1) and the SOT measures was computed for the entire sample to estimate the concurrent validity (average of 3 trials for BRU and SOT). Correlations were computed on 7 outcome measures including two measures from the BRU: sway area (SA), and sway velocity (SV); and 5 additional measures including filtered sway velocity (FSV), root mean square in the antero-posterior and medio-lateral directions (RMSap, RMSml), and peak to peak in the antero-posterior and medio-lateral directions (PTPap, PTPml). Nonparametric statistics were used since assumptions of normality were not met. A Spearman correlation coefficient of ≥ 0.75 indicates good to excellent relationship, 0.5-0.75 indicates moderate to good relationship, 0.25-0.50 indicates fair relationship, and 0.00-0.25 indicates little or no relationship.[343]

To examine group differences among sensory conditions to investigate age and disease effects, a nonparametric Mann-Whitney U test was used. because assumptions of normality were not met.

7.3 RESULTS

7.3.1 Reliability

Table 17 reports relative reliability (ICC) and absolute reliability (SEM) of sway area and sway velocity measures from the BRU (n= 90). Both ICC and SEM are calculated for sway area (SA) and sway velocity (SV) for all 6 sensory conditions (C1 to C6) in the BRU. The ICC for test-retest reliability were good to excellent for all outcome measures in all sensory organization conditions for the 2 consecutive times in the BRU (ICC range 0.64-0.87, $p < .001$).

Analysis of variance for absolute reliability was calculated for sway measures in all sensory control conditions in the BRU to provide a comparison of individual variability of performance across groups (Table 17). The SEM was small for all groups indicating high reliability for the instrument. Smaller SEM were found among the young healthy group (for sway area SEM < 1.0 all conditions except condition 5 and 6, SEM < 2.0 in conditions 5 and 6; for sway velocity, SEM < 0.2 all conditions except condition 5, SEM < 0.4 in condition 5). Larger SEM were found among the older healthy group (for sway area, SEM < 2.0 all conditions except 5 and 6, SEM range (3.0- 4.0) in conditions 5 and 6; for sway velocity, SEM > 0.4 conditions 4, 5, and 6).

Table 18 includes the evaluation of standard error of measurement proportion (SEM %), minimal detectable change (MDC95), and minimal detectable change proportion (MDC %) for both SA and SV measured for all 6 sensory organization in the BRU. The table shows the SEM standardized to the mean (SEM %) that allows a comparison of the magnitude of measurement error between the two different measures. The magnitude of measurement error associated with sway area was at least 20 % higher than the magnitude of measurement error associated with sway velocity across the 6 sensory control conditions. Smaller SEM% reflects lower measurement error.

Minimal detectable change values for SA are presented in Table 18, with the highest MDC scores for individuals with vestibular disorders, then older healthy, then younger healthy in all sensory control conditions. Conditions 5 and 6 show the highest MDC for all groups, and Condition 1 shows the smallest MDC for all groups. The MDC standardized to the mean (MDC %) allows the comparison of the magnitude of responsiveness between the two different measures (SA and SV) with smaller MDC% reflecting greater responsiveness. Sway velocity MDC% was at least 50% smaller than MDC% for sway area for all conditions.

7.3.2 Concurrent validity

All 90 subjects were tested in the SOT at the same day as the BRU. Significant moderate to excellent correlations ($p<.001$) were found between the BRU and the SOT in SA (all conditions), FSV (all conditions), RMSap (all conditions), RMSml (all conditions), PTPap (all conditions), and PTPml (all conditions) [Table 19]. The filtered sway velocity (FSV) showed stronger correlations compared to unfiltered (SV).

7.3.3 Group differences

Using the Mann-Whitney U test to compare the effect of age on SA and SV obtained from the BRU testing, the older healthy group had significantly higher SA and SV in all conditions ($p < .001$). Using the SOT to compare YH and OH, older healthy had significantly higher SA and SV in all conditions ($p < .01$) (Tables 5).

To investigate disease effect on sensory control, the YH group was compared with the young patient group (YP, n= 15) using the Mann-Whitney U test (Table 20). For the BRU, the amount of sway (SA and SV) for YP was significantly higher than amount of sway for YH ($p < .001$). The older healthy group was also compared with older patient group (OH, n= 15) and both the BRU and the SOT showed no significant differences between the two groups in SA and SV ($p >.05$) except condition one and two in the SOT.

For the SOT, the amount of sway (SA) for YP was significantly higher than amount of sway for YH ($p < .05$); amount of sway (SV) was significantly higher than amount of sway for YH ($p < .01$) in conditions 4, 5 and 6.

7.4 DISCUSSION

The reliability and validity of the BRU balance assessment module were established in this study. The BRU provides an accurate, reliable, and valid measure for sensory organization abilities using the HMD and foam as part of the balance assessment module for healthy persons and people with vestibular disorders. The BRU demonstrated strong reliability in most of the sway measures for the 6 sensory conditions. A strong positive correlation was found between the

BRU and SOT in almost all of the outcome measures. The BRU and SOT provided similar results about age and disease effect on sway measures during standing.

Previous studies have examined the reliability of the SOT. Wrisley et al (2007) examined the reliability of the SOT among young healthy subjects (21- 36 y). Intraclass correlation coefficients were fair to good for all conditions (0.43 to 0.79), except condition 3 where the ICC indicated poor reliability (0.35).[209] Cheryl et al (1995) examined SOT reliability among older healthy (65- 87 y). Intraclass correlation coefficients were fair to good for all conditions (0.43 to 0.70), except condition 3 with the ICC indicating poor reliability (0.15).[344] The BRU may be more reliable than the SOT especially for condition three. A learning effect may explain the poor reliability in condition three in the SOT. During condition 3 in the SOT, the subject can hear and see the movements of the surrounding walls. Subjects' reaction to the movement of the walls may be unreliable and difficult for the person to predict which may explain the poor reliability compared to the BRU.

The reliability of the BRU assessment module has not been studied previously. One study investigated the efficacy of using the BRU to discriminate between patients with relapsing-remitting multiple sclerosis (MS) with peripheral vestibular disorders and healthy older adults.[345] Subjects were tested in ten conditions; four conditions similar to Conditions 1, 2, 4, and 5 in our study; six more conditions included different optokinetic visual stimulations using the HMD. The MS group was significantly different in SA and SV from the control group in all conditions and the BRU was able to discriminate between the MS group and the control group.[345] In our study, I established the reliability of the BRU among healthy and patients with vestibular disorders for different age groups.

The size of SEM was largest for the patient group followed by the older healthy group and smaller for the young healthy group. The smaller SEM indicates a more reliable measure. The amount of variability expected from each group is one explanation for the SEM variation among study groups. Variability is expected to be higher among patients and older healthy groups compared with the young healthy group. Another interpretation for SEM differences among groups can be inferred from the Bland and Altman graph that shows that most of the subjects had smaller SEM; subjects who experienced high amounts of sway (patients, and older healthy) are more likely to show higher SEM (Figure 7-2).

Standard error of the measurement was highest during conditions 5 and 6 for all subgroups. Conditions 5 and 6 involve absent/inaccurate sensory information from both visual and somatosensory systems important for balance sensory control. Conditions 5 and 6 are the most difficult conditions in the test; the amount of sway expected during these conditions is high compared to the other conditions.

7.4.1 Concurrent validity

A strong relationship was found between the BRU and the SOT magnitude of sway for all study groups. A strong correlation was expected because both devices examine similar sensory organization constructs during standing. The psychometric properties of SOT including the clinical efficacy, cost effectiveness, validity, and reliability have been established.[202-208] Test-retest reliability of SOT among young healthy subjects (< 50 years), conditions 4-6, were fair to good reliability, range (0.35-0.79).[209] The SOT test-retest reliability, conditions 3-6, among elderly healthy individuals was measured; reliability was moderate to high, range (0.73-0.94).[210] The SOT correlated significantly with the following: Tinetti Balance Scale and functional measures of gait [346], post head shake test and caloric asymmetry symptoms [347], the Dizziness Handicap Inventory in patients with dizziness problems [348], and with lower extremities length and gait speed test.[349] The strong correlation between the BRU and SOT support the future use of BRU as a clinical tool in the management of patients with vestibular disorders.

7.4.2 Discriminant validity

Our final research goal was to examine group differences to investigate the effect of age and vestibular disease on balance (discriminant validity). Significant differences in sway measures between young and older healthy were found in both the SOT and the BRU suggesting that age is an important factor that influences balance. Studies have suggested that aging is associated with decline in structure and function of multisensory systems including somatosensory system, visual system, and vestibular system.[21, 22] Vibratory sensation, tactile sensation, and pressure sensation has been shown to be impaired with aging, especially in the lower extremities.[222-224] Studies also show that reduction of vestibular function with aging is associated with changes in the structure of the vestibular system. Rosenhall et al. reported that the vestibular system loses around 40% of the nerve and hair cells with > 60 years.[229] Reduction in the structure and function of the vestibular system among elderly people may increase COP sway, increase imbalance, and increase the probability of sensory conflict.[25] Elderly individuals are more likely to be dependent on sensory information from vision and vestibular systems and more likely to have peripheral neuropathy in the lower extremities.[25] Sparto et al. examined the amount of head sway associated with visual optic flow stimulation while standing on fixed or sway referenced support surface among young healthy, older healthy, and patients with unilateral vestibular loss.[350] The magnitude of sway in the older healthy group was significantly higher than the amount of sway in the young heathy group.[350] In another study, the amount of sway associated with an attention task increased significantly in the older healthy group compared with the young healthy group.[74] Our study findings were consistent with previous studies that show that in conditions where visual or somatosensation information was inaccurate for orientation in space, the amount of COP sway was greater in the elderly healthy group compared with young healthy group.[227, 228] In our study, COP magnitude of sway among older healthy was higher in all 6 sensory conditions.

To investigate the effect of vestibular disease on sensory control during standing, we compared young healthy with young patients (age < 60). The significant difference between the two groups in both the SOT and BRU in all sensory conditions suggests that objective ways for quantifying sway are helpful tools to investigate vestibular disorders effect on balance for subjects < 60 years. However, there was no significant difference in the amount of sway between the older healthy group and older patients. This result is consistent with the findings of Sparto et al., who found no difference in the amount of head sway associated with visual optic flow stimulation while standing on fixed or sway referenced support surface between older healthy and older patients with unilateral vestibular loss.[350] We were unable to explain the significant differences in the amount of sway between the older healthy and older patients in conditions one and two.

In our study, patients with vestibular disorders experienced difficulties in all sensory conditions. Patients with vestibular disorders when tested during conditions 5 and 6, where information from both vision and somatosensory are reduced or made inaccurate, COP sway increased and subjects experienced sudden falls.[232]

Subjects who have sensory selection problems are more likely to have balance problems in any condition or environment with inaccurate or absent sensory information. Not every subject with balance problems can be categorized as over-dependent on sensory information or as experiencing sensory conflict because of limited sensory organization abilities. Subjects may have difficulties selecting the appropriate sensory information for balance when exposed to any environment with inaccurate or absent sensory information for balance.[235, 236]

Examining balance in the 6 conditions of SOT and BRU may provide insights into the persons' ability to organize and select sensory information appropriate for balance which may demonstrate the type of environments and tasks responsible for imbalance. In situations where a subject falls or magnitude of sway increases with disruptions of somatosensory information from the lower limbs during standing on the foam (condition 4, 5, and 6), subjects may be considered surface dependent.[237] During conditions where magnitude of sway increase with inaccurate or no visual information using the HMD or with eyes closed (conditions 2, 3, and 6), subjects may be categorized as visually dependent.[237] A patient with vestibular disorder will experience increased sway or fall during conditions (4, 5, and 6) that involve disruptions of information from both visual and somatosensory systems. The subject may have sensory selection problem and may have an inability to correctly select sensory information for postural orientation if they experience large magnitude of sway in all situation involving disruptions of visual or somatosnesory information (conditions 3, 4, 5, and 6).[238]

7.4.3 Limitations and future work

The time between the BRU testing, retesting, and SOT testing was 15-20 minutes. The short time between test/retesting may affect the generalization of our study; a longer time (one day) may enhance generalization. The short time between the BRU testing and SOT testing may influence the subjects' performance on the second test.

Future studies may use the BRU to identify individuals with vestibular disorders, measure health outcomes after vestibular rehabilitation, and to customize vestibular rehabilitation programs for individuals with vestibular disorders. Using both the BRU and SOT, older healthy and older patients had similar sway; future research may use the BRU to add visual stimuli or a cognitive task, such as optokinetic stimuli, to increase the sensitivity of the test to discriminate disease effect among older subjects. The balance rehabilitation module in the BRU can also be investigated.

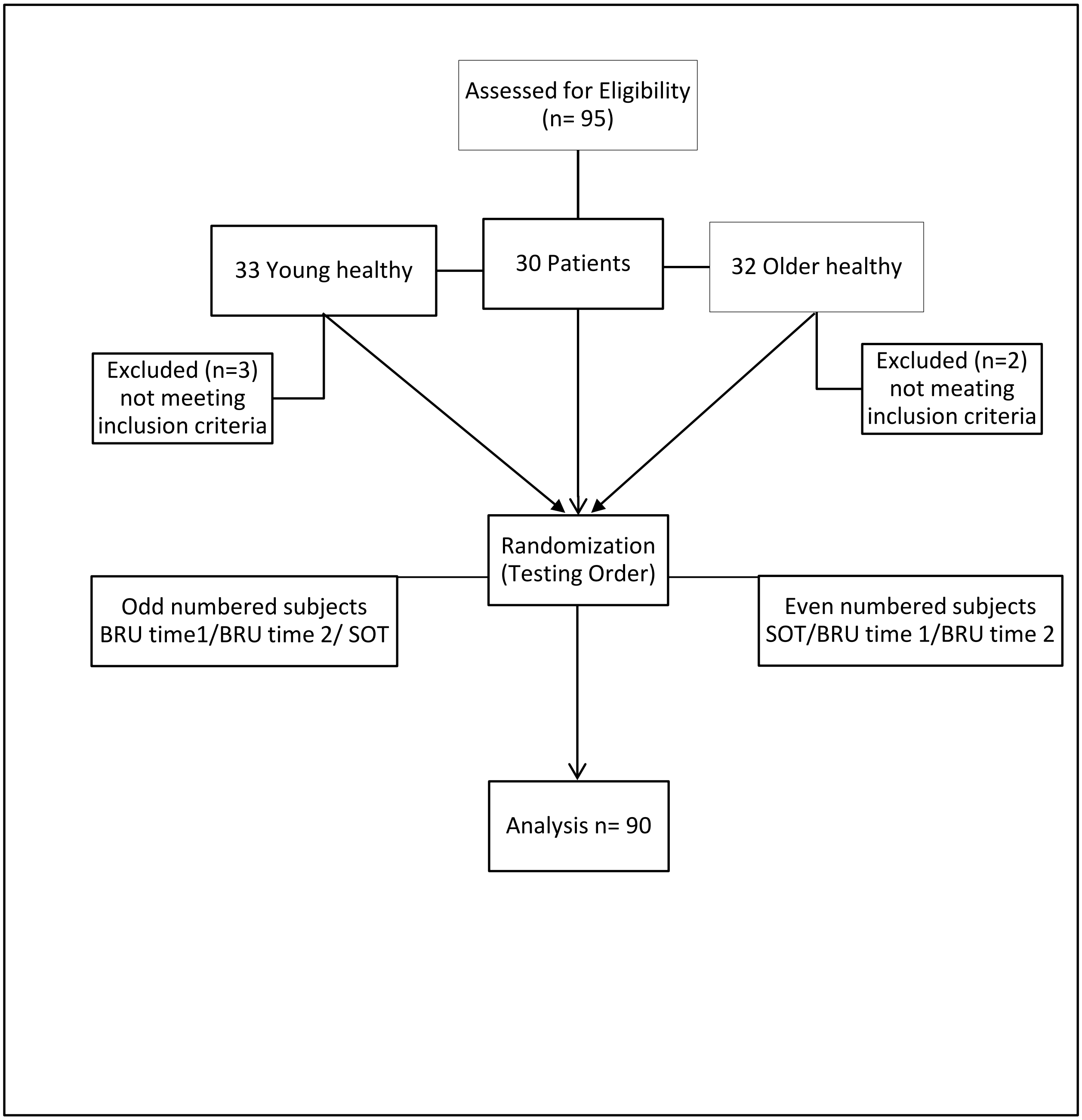

Figure 7-1: Participant flow diagram: includes number of subjects recruited, excluded/included in each group, tested, and included in the analysis

Table 16: Characteristics of all subjects including age, gender, duration of symptoms, and laboratory test results for patients (n = 90)

	Young Healthy	Older Healthy	Young Patients	Older Patients
Age (years)				
N	30	30	15	15
Mean ± SD	28.20 ± 6.06	77.2 ± 4.5	39.5 ± 10.8	65.5 ± 8.3
Range	19-45	68-85	25-55	56-81
Gender (Male;%)	17; 56%	12; 40%	5; 33%	5; 33%
Duration of symptoms (Months)	N/A	N/A		
Mean ± SD			42.7 ± 77.9	31 ± 42.6
Median			7.5	12
Range			1-240	1-132
Abnormal laboratory testing (n;%)	N/A	N/A		
Oculomotor			0; 0%	1; 6.7%
Positional			5; 33%	7; 46.7%
Calorics (reduced vestibular response)			7; 46.7%	8; 53.3%
Rotational Chair (decreased gain, asymmetry)			10; 66.7%	8; 53.3%
VEMPs			5; 33%	8; 53%

Laboratory testing included oculomotor testing, positional testing, caloric testing, rotational chair testing, and vestibular-evoked myogenic potentials (VEMPs).

Table 17: Intraclass correlation coefficient (ICC) and standard error of the measurement (SEM) of sway area (SA) and sway velocity (SV) measures from the Balance Rehabilitation Unit (BRU) (n= 90)

	ICC				SEM			
	ALL	YH	OH	P	ALL	YH	OH	P
SA_C1	0.74	0.49	0.71	0.72	0.78	0.45	0.78	1.04
SA_C2	0.84	0.82	0.61	0.83	2.22	0.36	1.21	3.75
SA_C3	0.68	0.50	0.60	0.64	1.66	0.91	0.85	2.61
SA_C4	0.84	0.85	0.74	0.84	1.77	0.53	1.60	2.61
SA_C5	0.74	0.74	0.72	0.69	5.01	1.94	3.34	7.74
SA_C6	0.68	0.71	0.62	0.66	6.43	1.64	3.53	5.33
SV_C1	0.82	0.68	0.72	0.81	0.26	0.12	0.21	0.41
SV_C2	0.80	0.61	0.68	0.79	0.60	0.14	0.38	0.99
SV_C3	0.64	0.74	0.83	0.53	0.46	0.13	0.19	0.79
SV_C4	0.82	0.86	0.69	0.81	0.41	0.13	0.41	0.63
SV_C5	0.82	0.68	0.85	0.76	0.62	0.38	0.42	1.02
SV_C6	0.87	0.84	0.74	0.88	0.41	0.19	0.50	0.51

Both SA and SV are measured for all 6 sensory conditions (C1 to C6) in the BRU. ICC and SEM are calculated for all subjects (ALL), young healthy (YH), older healthy (OH), and individuals with vestibular disorders (P). C1: (condition 1) involves standing on a firm surface eyes open looking forward; C2: (condition 2) involves standing on a firm surface with eyes closed; C3 (condition 3) involves standing on a firm surface looking at a visual world room (basket ball gym) displayed in the head mounted display (HMD) that sways with the subject; C4 (condition 4) involves standing on foam eyes open looking forward to the wall; C5 (condition 5) involves standing on a foam with eyes closed; C6 (condition 6) involves standing on a foam looking at the visual world displayed in the HMD that sway as the subject sways.

Table 18: Secondary analysis included evaluation of standard error of measurement proportion (SEM %), minimal detectable change (MDC95), and minimal detectable change proportion (MDC%) for both sway area (SA) and sway velocity (SV) measured for all 6 sensory conditions in the BRU

Sensory Condition	SEM%	MDC_{95}				MDC%
	All	All	YH	OH	P	All
SA_C1	56.46	2.16	1.24	2.15	2.87	156.51
SA_C2	82.91	6.17	1.01	3.34	10.41	229.81
SA_C3	69.70	4.61	2.53	3.01	7.22	193.21
SA_C4	45.01	4.90	1.48	4.45	7.24	124.77
SA_C5	48.11	13.88	5.39	9.26	21.45	133.35
SA_C6	50.89	10.72	4.53	9.77	14.76	141.06
SV_C1	27.47	0.72	0.32	0.57	1.13	76.13
SV_C2	43.20	1.65	0.40	1.07	2.74	119.74
SV_C3	37.22	1.28	0.35	0.53	2.18	103.18
SV_C4	25.75	1.13	0.35	1.14	1.73	71.37
SV_C5	22.92	1.71	1.05	1.17	2.83	63.52
SV_C6	17.65	1.14	0.53	1.38	1.42	48.91

C1: (condition 1) involves standing on a firm surface eyes open looking forward; C2: (condition 2) involves standing on a firm surface with eyes closed; C3 (condition 3) involves standing on a firm surface looking at a visual world room (basket ball gym) displayed in the head mounted display (HMD) that sways with the subject; C4 (condition 4) involves standing on foam eyes open looking forward to the wall; C5 (condition 5) involves standing on a foam with eyes closed; C6 (condition 6) involves standing on a foam looking at the visual world displayed in the HMD that sway as the subject sways.

Table 19: Concurrent validity of the Balance Rehabilitation Unit (BRU) in the assessment of balance in young healthy, old healthy, and in persons with vestibular disorders. Spearman rank order correlation (rho) between the BRU and the sensory organization test was calculated

		C1	C2	C3	C4	C5	C6	p (for all conditions)
SA	rho	0.67	0.81	0.74	0.62	0.64	0.67	**p < .001**
SV	rho	0.44	0.67	0.56	0.70	0.76	0.76	**p < .001**
FSV	rho	0.76	0.85	0.72	0.74	0.72	0.74	**p < .001**
RMSap	rho	0.57	0.80	0.67	0.48	0.50	0.45	**p < .001**
RMSml	rho	0.64	0.76	0.71	0.63	0.61	0.65	**p < .001**
PTPap	rho	0.57	0.80	0.67	0.58	0.58	0.57	**p < .001**
PTPml	rho	0.65	0.72	0.68	0.65	0.64	0.68	**p < .001**

C1: (condition 1) involves standing on a firm surface eyes open looking forward; C2: (condition 2) involves standing on a firm surface with eyes closed; C3 (condition 3) involves standing on a firm surface looking at a visual world room (basket ball gym) displayed in the head mounted display (HMD) that sways with the subject; C4 (condition 4) involves standing on foam eyes open looking forward to the wall; C5 (condition 5) involves standing on a foam with eyes closed; C6 (condition 6) involves standing on a foam looking at the visual world displayed in the HMD that sway as the subject sways; p: significance for all conditions; SA: sway area; SV: sway velocity; FSV: filtered sway velocity calculated at university of Pittsburgh; RMSap: root mean square calculated in the anterior-posterior direction; RMSml: root mean square calculated in the mediolateral direction; PTPap: peak to peak calculated in the anterior-posterior direction; PTPml: peak to peak calculated in the mediolateral direction.

Table 20: A nonparametric statistic (the Mann-Whitney U test) was used to compare the young healthy (YH) (n= 30), older healthy (OH) (n= 30), young patients (YP) (n= 15), and older patients (OP) (n= 15) sway data for sensory conditions 1-6 in both the BRU and SOT

				C1	C2	C3	C4	C5	C6
BRU	SA	YH (n=30)	OH (n=30)	**p= .003**	**p= .001**	**p= .001**	**p < .001**	**p= .001**	**p= .001**
		YH (n=30)	YP (n=15)	**p < .001**	**p < .001**	**p < .001**	**p= .001**	**p= .001**	**p= .001**
		OH (n=30)	OP (n=15)	p= .555	p= .258	p= .324	p= .665	p= .700	p= 1.00
	SV	YH (n=30)	OH (n=30)	**p < .001**	**p < .001**	**p < .001**	**p < .001**	**p < .001**	**p < .001**
		YH (n=30)	YP (n=15)	**p < .001**	**p < .001**	**p < .001**	**p= .001**	**p= .001**	**p= .001**
		OH (n=30)	OP (n=15)	p= .360	p= .268	p= .379	p= .102	p= .312	p= .354
SOT	SA	YH (n=30)	OH (n=30)	**p= .006**	**p= .003**	**p= .002**	**p= .001**	**p < .001**	**p < .001**
		YH (n=30)	YP (n=15)	**p= .046**	**p < .001**	**p= .002**	**p < .001**	**p < .001**	**p < .001**
		OH (n=30)	OP (n=15)	p= .163	p= .828	p= .736	p= .202	p= .075	p= .324
	SV	YH (n=30)	OH (n=30)	**p < .001**	**p < .001**	**p < .001**	**p < .001**	**p < .001**	**p < .001**
		YH (n=30)	YP (n=15)	p= .847	p= .065	p= .360	**p= .002**	**p= .004**	**p < .001**
		OH (n=30)	OP (n=15)	**p= .004**	**p= .016**	p= .090	p= .800	p= .847	p= .112

C1: (condition 1) involves standing on a firm surface eyes open looking forward; C2: (condition 2) involves standing on a firm surface with eyes closed; C3 (condition 3) involves standing on a firm surface looking at a visual world room (basket ball gym) displayed in the head mounted display (HMD) that sways with the subject; C4 (condition 4) involves standing on foam eyes open looking forward to the wall; C5 (condition 5) involves standing on a foam with eyes closed; C6 (condition 6) involves standing on a foam looking at the visual world displayed in the HMD that sway as the subject sways.

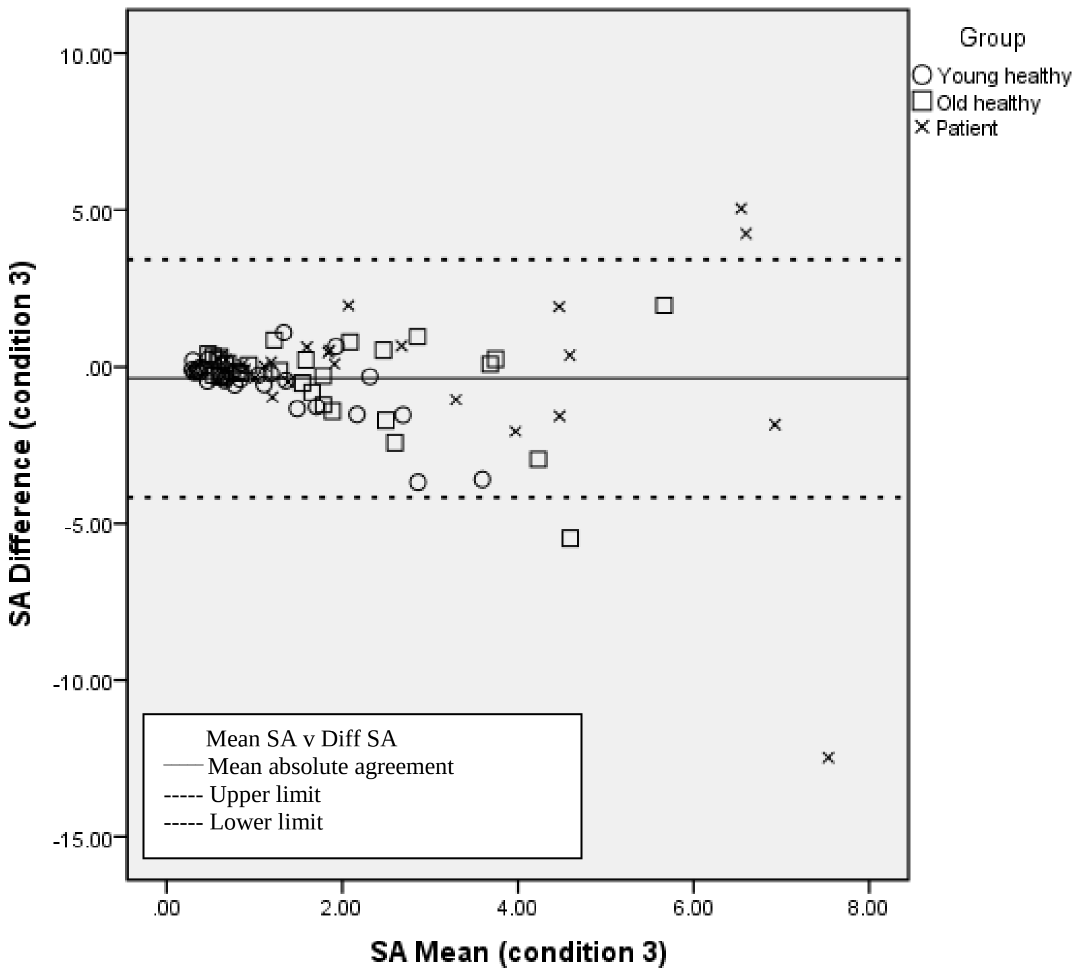

Figure 7-2: Sway area (SA) mean value (Time 1, Time 2), and difference (Time 1 – Time 2) with mean absolute agreement and upper and lower limits of agreement indicated by unbroken and dashed lines, respectively

The line in the middle is the mean between time 1 and 2, subjects scores vary around the mean, variation is small with young healthy and bigger with old healthy and patients.

8.0 GENERAL DISCUSSION

In this dissertation, I extended the work of previous groups that have used technology-based visual stimuli for habituation of dizziness symptoms. I explored the effect of VRBT on self-report and performance measures and explored the use of VRBT as an intervention for individuals with vestibular disorders. Our study findings suggested that subjects improved significantly and maintained improvements in self report and performance measures. Subjects reported symptoms increased during treatment sessions, but overall reports of symptoms reported during treatment sessions reduced from session 1 to session 6 suggesting long term habituation. Furthermore, the symptom reduction from session 1 to session 6 was associated with increases in the intensity and complexity of the visual stimuli provided in terms of optic flow velocity and product density. Virtual reality based therapy may be a promising new intervention for individuals with vestibular disorders that may be used as a tool to provide habituation exercises.

I also examined the difference in self report and performance measures between customized physical therapy and VRBT in persons with vestibular disorders. Our study findings suggested that both groups (PT and VRBT) improved significantly and maintained improvements for six months. Both interventions provided equivalent outcomes. The virtual reality based therapy appeared to improve symptoms of individuals with vestibular disorders at least as much as customized physical therapy. However, currently the cost and effort of using VRBT is high compared to PT, so there is no advantage of using VRBT.

In the second part of this dissertation, I established the reliability and validity of the BRU as a tool for balance assessment. The BRU demonstrated strong reliability in sway measures, and provided a valid measure for balance using the HMD and foam among healthy persons and people with vestibular disorders. A strong relationship was found between the BRU and SOT for all groups in sway measures. The BRU was able to discriminate age effect and vestibular disease effect on balance. The BRU is another example of virtual reality based therapy technology that may provide visual stimuli using cheaper methods such as an HMD. The BRU takes less space, is a cost effective method of proving virtual reality based therapy stimulation compared to a virtual reality based therapy cave and can be used for balance assessment.

8.1 LIMITATIONS/ OBSERVATIONS

The difficulty in the recruitment varied between the virtual reality based therapy and the BRU studies. In the VRBT study, I recruited 40 subjects over the course of four years; the recruitment of subjects who met the criteria was difficult. In the virtual reality based therapy study, people seemed not interested to make a commitment to attend the three hours of assessment before, after, and at the 6 month follow up and commit to coming to physical therapy each week for 6 weeks. In the BRU study, I recruited 90 subjects over the course of 6 months. The recruitment procedure was easier in the BRU study possibly because the study involved one session and subjects were tested the same day that they came to the clinic to see the doctor for their diagnosis.

For the BRU study, there were multiple things that delayed the start of the study. . The BRU was initially developed outside the United States, and there were no training programs in the United States for using the BRU. The primary investigator (K.A) had to travel to Uruguay for a week and received training on the BRU from experienced clinicians in Uruguay. It took about 3 months to obtain a visa in order to be able to travel for the training. After training was completed, it took another 4 months to ship and install the device at the Eye and Ear Institute in Pittsburgh.

8.2 FUTURE WORK

Future studies may compare three interventional groups (VRBT, customized physical therapy group, and combination of VRBT and customized physical therapy). Future VRBT studies should consider using less expensive and smaller technology such as HMD.

Future studies may compare the use the rehabilitation module in the BRU to provide visual stimulation using the HMD in the rehabilitation of individuals with vestibular disorders. A second step may be to compare three groups (customized physical therapy (PT), BRU rehabilitation combined with PT, and BRU rehabilitation only). The BRU assessment module may also be used to provide outcome measures after vestibular rehabilitation and to customize vestibular rehabilitation programs for individuals with vestibular disorders.

Other future studies may investigate use of the BRU to investigate the influence of different visual stimuli, such as optokinetic stimuli, using the HMD on balance and postural control. The balance rehabilitation treatment module in the BRU can be investigated in future work.

9.0 CONCLUSION

Virtual reality based therapy may be a promising new intervention for individuals with vestibular disorders that can be used as a form of habituation training for symptoms induced in visually complex environments. However, the cost and effort of using VRBT is high compared to customized physical therapy. So there is no advantage of using VRBT since the results were similar to the customized physical therapy.

The BRU provides a new tool for balance assessment that records postural sway in both the medio-lateral and anterior posterior directions. The strong correlation between the BRU and SOT in almost all of the outcome measures indicated that the BRU provided similar results about age and disease effect on balance during standing.

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