The Potential Use of Virtual Reality in Vestibular Rehabilitation: Preliminary Findings with the BNAVE

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Abstract
In this paper, the potential use of virtual reality for use with persons with vestibular disorders is discussed. The limitations of existing physical therapy for persons with vestibular disorders are detailed. Explanations are provided about why the use of virtual reality might be effective with persons with vestibular disorders. A newly designed virtual reality device, a balance near automatic virtual environment (BNAVE), was used in a pilot study to determine the effect of a moving visual scene in persons with and without vestibular pathology. The postural sway of two patients and three controls were compared. Persons were asked to stand while viewing a sinusoidal waveform on a force plate. Postural sway was increased in both young and older adults in the immersive virtual environment. These preliminary data suggest that the virtual environment produced by BNAVE was valid.

INTRODUCTION

The use of virtual reality (VR) to enhance vestibular rehabilitation is a relatively new concept.[1-4] The novel aspect of using virtual reality in physical therapy vestibular intervention is that one can bring "real" world situations instantaneously into the clinic. Virtual reality devices have decreased in price -making the idea of their use exciting for physical therapists. The application of this new technology, however, should be based on a sound theoretical rationale and optimally enhance existing interventions. In this paper we 1) discuss why virtual reality might be helpful as a therapeutic adjunct to vestibular physical therapy, 2) present a rationale for how virtual reality may enhance vestibular rehabilitation, through stimulation of retinal slip[5,6,7] and habituation to specific conditions[8,9] and 3) report on preliminary findings of 2 persons with vestibular dysfunction with age matched controls using a virtual reality cave device.

VESTIBULAR DISODERS AND THEIR MANAGEMENT

Symptomatology of Vestibular Disorders

Usually, persons with peripheral vestibular disorders have disequilibrium and complain of visual blurring.[10] These common symptoms may be caused by abnormalities in the vestibulo-ocular reflex (VOR) during head movements. In acute peripheral vestibular injuries or insults, the VOR may decrease in efficacy by as much as 75% when the head is moved toward the injured side and by as much as 50% toward the non-affected side.[11] Patients can learn to adapt to vestibular injuries using vision, particularly visual motion induced by active head movement.[6,12] The more a person with vestibular dysfunction moves, generally, the faster they improve.

Disturbances of gait can be a direct result of an acute peripheral or central vestibular disorder. Such patients typically veer when walking, may have a wide-based gait, and have great difficulty walking while simultaneously attending to movement in the periphery. Persons with peripheral vestibular injuries may be grossly unstable until they can adapt. Typically, persons with peripheral vestibular disorders respond by restricting head and trunk movement during gait and upright stance to avoid dizziness and to remain more stable.[10] This strategy of not moving does not promote long-term adaptation. Persons referred earlier to vestibular rehabilitation demonstrate less disability and better outcome.[13]

Persons with chronic vestibular disorders often develop psychological complications.[14,15] Primary among these complications are panic or anxiety, avoidance behaviors, and also a preoccupation with their health. Nazareth et al[16] report that there were three predictive factors of dizziness 18 months after onset: a history of fainting (probably a symptom of panic), vertigo, and avoidance of situations that provoked dizziness.

Limitations of Vestibular Physical Therapy

The goal of vestibular physical therapy is to create situations that will stimulate patients' symptoms in order to promote habitutation. Vestibular exercises progress from simple movement in simple environments to complex movements in complex environments. Physical therapists generally try to increase the difficulty of the exercises by moving from slow to fast, from sitting to standing, from a wide-based stance or wide-based gait to a narrow-based stance or gait, and from head/trunk stability to movement of the head and trunk, with the ultimate goal of being able to move the head and trunk while ambulating. In addition, another consideration in treatment planning is the concept of enriching the visual scene as the exercises are performed. Generally, physical therapists attempt to start vestibular exercises near blank or white walls and then increase the difficulty of the task by making the environment more visually complex.

Patients are frequently asked to perform eye/head movements in different postures while staring at a checkerboard or a bull's eye type pattern. Usually, they start these exercises in the sitting position and then progress to standing and ultimately to walking. One of the problems with these progressions is that it takes time for the patient to advance.

USE OF VR FOR PATIENTS WITH VESTIBULAR DISORDERS

Viirré[1-3] and Kramer et al[4] were the first to discuss the use of VR with persons with vestibular disorders primarily via the VOR. Viirré[1,2] suggested that VR could be used to increase the rate of adaptation by specifically adapting scenes to a person's capabilities, thereby facilitating faster recovery. Viirré[3] suggests that the VOR can be adapted with VR stimulation with an increase in the VOR gain.[45] Changes in VOR sensitivity have been reported using VR stimuli that gently challenge the VOR.

We speculate that the use of VR, will allow patients to progress more rapidly through existing vestibular physical therapy rehabilitation protocols. VR may also facilitate the use of objective data to indicate when the patient is ready to advance. Currently, decisions as to when to advance a patient's exercise program are based solely on the judgment of an experienced clinician. It may be possible to develop objective criteria that the therapist can use to advance the patient in a safe manner. In addition, in virtual reality therapy one can safely control interactions with the virtual environment without real world hazards.[17] VR encourages self-directed learning and allows a level of control not possible in the "real" world.[17]

Rationale

A primary rationale for using virtual reality for vestibular rehabilitation is that realistic visual environments may promote adaptation by causing retinal slip. Retinal slip, i.e. movement of a visual image across the retina, is a powerful signal that can induce adaptation of vestibular responses as the brain attempts to stabilize gaze in order to minimize the retinal slip.[5] Using retinal slip to speed compensation is based on several animal models.[18,19] Recovery of the VOR requires both visual inputs and movements of the head and body.[6,7,20,21] For example, in cats and monkeys, the gain of the VOR does not recover in animals that are kept in the dark after a unilateral labyrinthectomy.[20,21] VOR recovery only begins when animals are provided light. In addition, when animals are not allowed to move after a unilateral vestibular nerve section, there is a delay in the recovery of their postural control and their recovery time is longer.[22] Therefore, exposure to visual experiences and movement appear to be key to the functional recovery of persons with vestibular disorders.

Retinal slip can be induced in a quantifiable manner in persons with both acute and chronic injuries to attempt to promote adaptation. The ability to quantify a patient's physiologic responses, such as postural sway, and a patient's perceptions can increase our knowledge of the rehabilitation process. Virtual reality may permit the study of how persons with vestibular disorders learn to compensate for their dysfunction in a very safe and controlled environment.

A randomized trial has demonstrated that persons with uncompensated peripheral vestibular disorders can improve with vestibular rehabilitation directed at inducing retinal slip.[23, 24] Several groups[23, 25, 26] have included as part of the exercise program eye and head movements and exposure to a large-field optokinetic stimulus. Persons were exposed to moving stripes with different amounts of light, at different speeds, during head movements, on different support surfaces including foam and during gait. Pavlou et al[24] studied persons with uncompensated unilateral peripheral vestibular dysfunction using a customized exercise program and a machine-based optokinetic stimulation exercise program. Preliminary findings suggest that patients improved with both, yet the machine-based group demonstrated greater improvement. Pavlou and colleagues[24] suggested that physical therapy involving conflicting visual environments may be more effective than a customized program alone or a program that includes only Cawthorne-Cooksey exercises.[27, 28] Virtual reality scenes may promote rehabilitation more effectively than optokinetic-based therapies since there is an ability to finely control the virtual scene.

Immersion in a virtual environment may be ideal for promoting habituation. Habituation refers to reducing a patient's symptoms by performing the specific movements that provoke their symptoms repetitively and very quickly.[8] It has been suggested that habituation exercises can reduce symptoms in persons with vestibular disorders. Typically, there is a graded type exposure that the patient is guided through by the physical therapist to encourage the patient to experience situations and positions that increase their symptoms. At the beginning of habituation therapy, patient's symptoms may get worse as they are moved very quickly into various functional positions that provoke their symptoms.[8] Little is known about the mechanism of habituation. One hypothesis is that active movement presents a sensory mismatch to the brain that promotes compensation and adaptation for labyrinthine disorders.[9]

Virtual Reality and Vestibular Rehabilitation

The use of virtual reality as a possible intervention for treating persons with vestibular disorders is based in part on its successful application in the treatment of mental disorders during the last decade. Drs. Rothbaum and colleagues have performed virtual reality exposures to complex visual scenes since 1993 to treat psychological dysfunction. The treatment of acrophobia was their first controlled study.[29] Participants were repeatedly exposed to virtual footbridges of varying heights and stability, outdoor balconies of varying heights, and a glass elevator that ascended 50 floors. VR exposure was effective in significantly reducing fear of and improving attitudes toward heights. Anxiety, avoidance, distress, and fearful attitudes toward heights decreased significantly for the VR exposure group but not for the control group.

In a later study, Rothbaum et al[30] attempted to treat persons with the fear of flying and demonstrated in a case report that virtual reality could be used effectively to treat fear of flying disorder. Typical exposure therapy is used to treat persons with phobic avoidance. Often it is comprised of asking the patient to expose themselves to gradually more difficult situations that approach the circumstances that they are avoiding. A Phase I National Institutes of Mental Health study devoted to testing the feasibility of VR exposure as applied to fear of flying has recently been completed.[31] The relative efficacy of VR exposure versus standard exposure therapy (i.e., going to the airport) as compared to a wait list (WL) control group was tested. During VR exposure sessions, patients wore a head-mounted display with stereo earphones that provided visual and audio cues consistent with being inside the passenger compartment of an airplane. VR exposure was provided twice weekly. Results indicated that VR exposure and standard exposure were both superior to the control condition, with no differences between VR and standard exposure. As compared to controls, subjects had a decrease in symptoms as measured by standardized questionnaires, had less anxiety during an actual flight, had greater number of participants who would attempt an actual flight, and had better self-ratings of improvement. The gains observed in treatment were maintained at a six-month follow-up.

With regard to vestibular rehabilitation, the concept of standard exposure therapy has been used with patients with dizziness and agorophobia.[32] Persons with dizziness and agorophobia improved their Hamilton anxiety rating scores[33] with exposure therapy combined with physical therapy intervention. The idea of exposing persons with space and motion discomfort[34] to increasingly more difficult visual scenes under controlled conditions is a potential use of the virtual reality technology.

Many patients with vestibular disorders complain of "space and motion discomfort" (SMD).[29,34-39] Patients often tell the physical therapist that they have dizziness in situations with excessive sensory stimulation in the periphery. Grocery stores and shopping malls are two of the most difficult situations for persons with SMD. Cohen et al[40] and Cohen & Kimball[41] included grocery stores as part of their activities of daily living assessment pre- and post- therapy intervention. However, it is impractical for a physical therapist to monitor a patient's performance in real-life situations.[30] The therapist must rely on the patient's perception of the experience after the fact. These perceptions may or may not be an accurate reflection of how the patient actually felt, which is why recording objective and subjective data, eg. anxiety levels, during VR exposures in persons with vestibular disorders is important.

Exercises currently used by physical therapists may be easily adapted and enhanced in a VR environment. For example, physical therapists use a checkerboard in order to make the eye head exercises more difficult. A checkerboard scene (Figure 1) has been designed that is similar to what it frequently used in physical therapy. Future plans include the development of a virtual reality grocery store since grocery shopping is such a provocative situation for persons with vestibular disorders. The grocery store scene will be more interesting and motivating than a black and white checkerboard scene.

VR allows the physical therapist a degree of control over the environment that is not normally possible.[42-44] VR exposure can be instituted systematically and carefully to ensure that the patient is comfortable and safe.[17,44] It is also the only method whereby a patient can be exposed to life like scenes of increasing complexity while being closely monitored for safety.[30,44]

DEVELOPMENT AND TESTING OF THE BNAVE PROEJCTED ENVIRONMENT

A spatially immersive VR system has been developed to investigate the multi-sensory interactions in postural control. The BNAVE (Balance Near Automatic Virtual Environment), allows us to present sensory conflict and congruent visual inputs to subjects, with response measures currently including postural sway, head motion, and electromyography (EMG). It was built in collaboration with Dr. Hodges based on the NAVE (Near Automatic Virtual Environment) at Georgia Tech. This basic research facility is similar to the CAVE (CAVE Automatic Virtual Environment) developed at the University of Illinois.[45]

The BNAVE is a stereoscopic, projection-based system with 2.4m high by 1.8 m wide screens on three sides to encompass a subject's entire horizontal field of view (FOV) when looking forward and is 2.6 meters high. (Figures 2 & 3) The BNAVE display has a viewing angle of 200 degrees horizontally and 95 degrees vertically. A VREX 2210 LCD-based stereoscopic digital projector controlled by an Intel PIII computer produces each screen's display. The computers are connected to a primary controlling computer via a standard Ethernet. The primary computer coordinates scene generation and controls data collection. Coordination of the scenes is performed using a display application written by the Virtual Environments Group at Georgia Tech.

Use of virtual reality has some advantages over real world vestibular training. In the VR world there is greater flexibility and control as one can manipulate the complexity of the environment by changing visual demands and lighting. Visual presentation can be monoscopic or stereoscopic. From a measurement standpoint it is reliable for consistent presentation. Feedback is immediate. Programs can be customized, initiated and terminated quickly based on patient's symptoms. The VR environment is potentially safer than real world environments.

The disadvantages are that the individual may be more comfortable in the VR world and performance wont transfer there is some visual distortion and delay or limitation to the visual scene. Developing the software and installing and running some equipment is expensive and time intensive. Visual stress and motion sickness are side effects.

A projection-based spatially immersive system was chosen over a head-mounted display (HMD) system commonly used in VR for several reasons. A primary reason is the large field of view available in the BNAVE is not currently available in the commercially available and affordable HMDs on the market (typical field of view is 30 degrees). Peripheral motion cues appear to represent an important variable in the stabilization of posture. Other advantages and disadvantages of using a spatially immersive display versus a HMD are listed in Table 1.

Preliminary Findings

To test the validity of BNAVE's immersion a pilot study was performed. Five adult subjects volunteered to participate in a pilot experiment approved by the University of Pittsburgh Institutional Review Board after providing informed consent.

Subjects: Two subjects had a peripheral vestibular disorder (PVD) confirmed with laboratory vestibular testing, and three served as control subjects. Controls had all undergone vestibular testing and had normal age adjusted hearing, a normal ENG (oculomotor and calorics), normal age adjusted computerized dynamic posturography scores, and normal rotational chair results. In addition, all subjects had a normal neurological examination as performed by a neurologist. The age and gender of the five subjects were: a younger adult with a peripheral vestibular disorder (31 y.o. male), an older adult with a peripheral vestibular disorder (71 y.o. male), two younger adult control subjects (31 y.o. male, 40 y.o. female), and an older adult control subject (67 y.o. female).

Methods: Subjects viewed one of three environments: 1) room lighting, nothing displayed on screens, 2) infinite tunnel, 2 squares per meter, sinusoidal velocity profile, and 3) infinite tunnel, 2 squares per meter, pulse velocity profile.

Subjects removed their shoes, donned the head sensor, and stood on a force platform with their feet comfortably apart. To prevent a potential fall, they wore a harness that was secured to a support above the BNAVE. Subjects viewed two types of scenes with the room darkened. One scene consisted of an infinitely long checkerboard tunnel that moved backward and forward in a sinusoidal fashion. The second scene moved backward and forward at constant velocity (pulsed). The 60-second trials consisted of 40 seconds of scene movement preceded and followed by 10 seconds of no scene movement. Periods of rest were interspersed to prevent fatigue. The dependent variables included the anterior-posterior (AP) movement of the center of pressure (COP), head movement, and eye movement. The center of pressure was measured using a force platform and head translation was measured using an electromagnetic position and orientation sensor that was affixed to an adjustable plastic headband that was placed comfortably on the head. The data from the force platform and head sensor were sampled at 120 Hz.

Results: The anterior-posterior (AP) movement of the head during a sinusoidal velocity profile trial for the older control subject is show in Figure 4A. A periodic response occurring at the same frequency as scene movement can clearly be observed in head translation. Root-mean-square (RMS) values were computed for the pre-, during-, and post- movement periods. Portions of these data are summarized in Figure 4 (B). This graph shows the RMS value of the head translation during the tunnel movements relative to the RMS value computed during the pre-movement baseline period. Substantial increases in head movement were obtained. The older subjects responded with greater sway than the younger subjects.

AP movement of the COP during a pulse velocity trial for a young control subject is shown in Figure 5. For clarity, only 40 seconds of the recording is shown. During the pulse velocity trial, movement of the COP in the direction of the tunnel movement can be seen after the initiation of the tunnel motion (indicated by solid vertical bars).

The peak and total sway response due to the pulse velocity scene movement for the COP data shown below were quantified. In the 10 seconds prior to scene movement, the peak sway was 0.8 cm and the total sway response was 3.3 cm-s. During the 10 seconds of scene movement, the peak sway increased to 1.9 cm and the total sway response increased to 9.2 cm-s.

Interpretation: These preliminary data suggest that postural sway is affected in young and older persons with and without vestibular disorders by visual scene movement in an immersive virtual environment. The persons with vestibular dysfunction were well compensated and at least 1 year post acoustic neuroma resection. Future plans include testing persons with acute vestibular dysfunction. Persons with long-term peripheral loss were chosen first in order to determine if the virtual reality exposure was safe for people with vestibular loss.

SUMMARY

Vestibular disorders are associated with significant disability, especially an increased risk of falls. Vestibular rehabilitation therapy has been shown to be helpful for patients with balance disorders. However, vestibular therapy has several limitations, particularly related to quantifying the physical therapy interventions and deciding when to increase the difficulty of a patient’s exercise regimen. Based upon favorable results of others using VR therapy for adapting the VOR and for several related disorders, VR appears to have the potential to address some of the limitations of vestibular rehabilitation therapy. Specifically, VR can be used to create increasingly challenging environments in a controlled and safe setting. The principles of retinal slip, habituation, and graded exposure can all be systematically applied in the rehabilitation of persons with vestibular disorders through the use of virtual reality. It is not known if there is long-term benefit from virtual reality exposure. However, the virtual reality technology exists and may prove to be a valuable adjunct to existing balance rehabilitation therapy.

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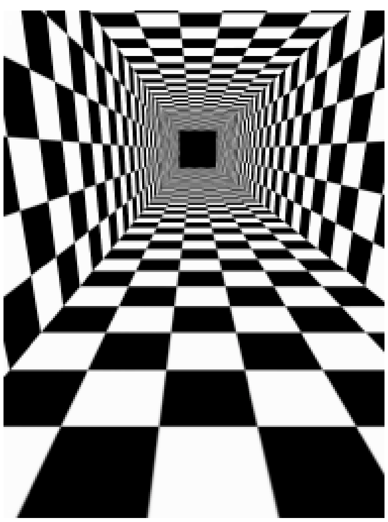
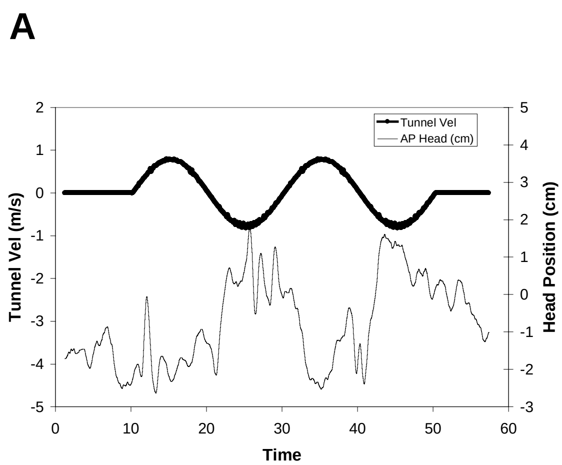


Figure 1. The configuration of the rectangles consisting of checkerboard surfaces on three walls of the BNAVE that surround the subject.

Figure 2. The BNAVE with a person surrounded by the 3 sides with a virtual image.



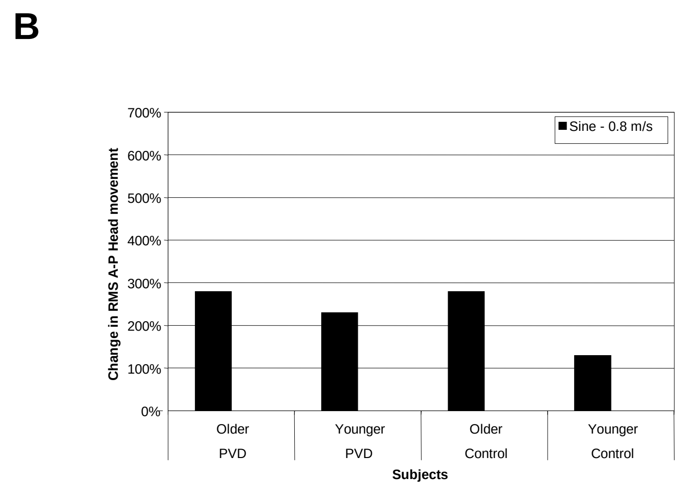


Figure 4. A) Head movement profile obtained from an older control subject while viewing a scene moving with a sinusoidal velocity profile (0.05 Hz, 0.6 m/s rms velocity) B) RMS values of antero-posterior head movement relative to the pre-movement baseline (PVD= a person with peripheral vestibular disease).

Figure 5. Anterior-posterior center of pressure (AP COP) and tunnel velocity movement profile for a pulse velocity condition. Vertical bars indicate start of tunnel movement. Tunnel velocity scale on left and AP COP scale on right of each graph.

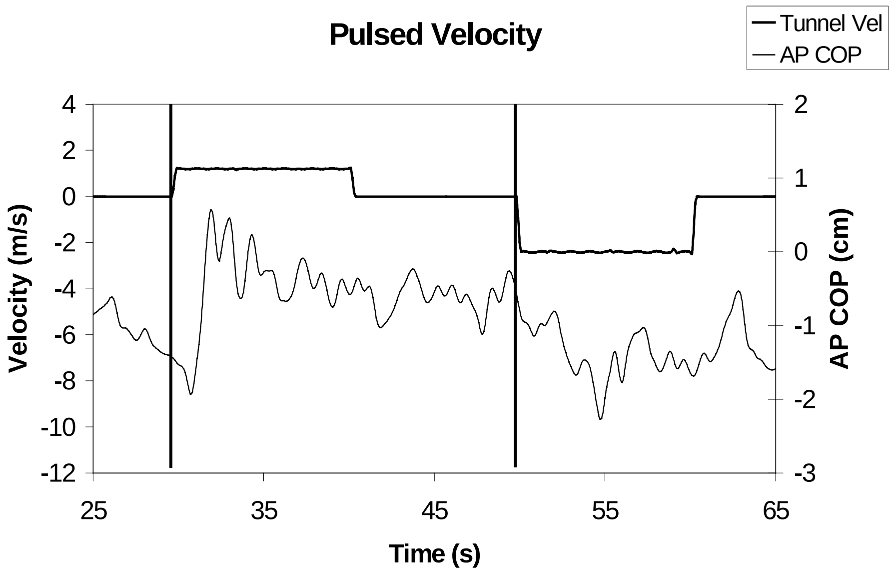


Table 1. Advantages and Disadvantages of a Head Mounted Device (HMD) versus a spatially immersive display (SID), such as the BNAVE.

	HMD	BNAVE or SID
Visual scene	Viewed in all directions [46,47]	Unable to look up or behind [48]
Field of view	Narrow (30° horizontal)	Large (200° horizontal)
Therapist's View	May not correspond with the patient	Corresponds with the patients
Cost	Expensive [49]	Much more expensive [50]
Weight on the head	Greater	Lesser
Space requirements	Small	Very large
Visual Stress	Known reports [51,52]	Unknown
Motion Sickness	Many reports	Few reports