5-2019

Subjective Visual Vertical and Otolith Compensation: Evaluating Off-Axis Rotation Stimulus in Healthy Controls

Eva Price

Abstract

The vestibular system senses changes in head position and is responsible for the brain's perception of verticality. Vestibular dysfunction is caused by deficits in the semicircular canals and/or otolith end-organs with resulting symptoms including dizziness, vertigo, and unsteadiness. Current vestibular rehabilitation focuses on compensation of the semicircular canal-mediated vestibulo-ocular reflex through gaze and balance exercises. Little is known about rehabilitation of otolith organ function, yet research findings suggest that fall risk may be related to otolith dysfunction. A recent case study demonstrated improvement of vertical perception and balance following off-axis rotation in a rotary chair, showing that such stimulation may be useful for compensation of otolith organ dysfunction. The purpose of our research was to further investigate off-axis rotation as a possible treatment method by evaluating subjective visual vertical (SVV) in healthy controls. Two distance parameters (3.5 cm off-axis and 7.0 cm off-axis) were applied to the rotary chair, with results measured through the SVV test, visual analog scales (VAS), and the balance tilt test (BTT). The magnitude of SVV shift following off-axis rotation was measured in both the 3.5 cm and 7.0 cm off-axis experiments. The greater distance parameter (7.0 cm) did not increase SVV shift magnitude more than the 3.5 cm parameter; yet, resulted in greater symptom intensity as measured through the VAS. These findings led to the conclusion that a distance parameter of 3.5 cm off-axis is optimal for stimulating the otolith organs. This discovery may be helpful in future research utilizing off-axis rotation as a possible treatment method for vestibular patients suffering from otolith dysfunction.

Table of Contents

Abstract 2

List of Tables 4

List of Figures 5

Introduction and Literature Survey 7

A. Role of vestibular system in human function 7

B. Vestibular hypofunction 7

C. Vestibular organs involved 9

D. Standard vestibular rehabilitation 12

E. Evidence for otolith compensation 13

F. Conclusion and Purpose 14

Methods 15

Results 24

Discussion 30

References 33

List of Tables

Table 1. Control: group means (SD) and min/max values of SVV for Session 1 versus Session 2. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift. 16

Table 2. Duration of the rotation cycle 19

Table 3. Exp. 1A (3.5 cm off-axis rotation): group means (SD) and min/max values of SVV for pre- versus post-OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift. 25

Table 4. Exp. 1B SVV values: pre- versus post-OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift. 25

Table 5. OAR versus Control: SVV absolute differences 29

Table 6. Exp. 1A comparison of BTT pre- versus post-OAR total values. 30

Table 7. Exp. 1B comparison of BTT pre- versus post-OAR total values. 30

List of Figures

Figure 1. Side view of the Neuro Kinetics I-Portal® NOTC rotary chair, which is enclosed in a completely light-tight, darkened rotary chair booth during rotation..... 17

Figure 2. The I-Portal Falcon high speed video-oculography (VOG) system (100 Hz frame rate) for evaluation and recording vertical, horizontal, and torsional eye movements in collaboration with the VEST 8.0.1 operating and analysis software system. 17

Figure 3. A person secured in the rotary chair, holding two handles with buttons to press for subjective visual vertical (SVV) adjustments. During rotation and SVV trials, the rotary chair booth was completely darkened to eliminate all visual cues other than those provided by the laser target during the experiment. 18

Figure 4. A vertical 10-cm line was used as a visual analog scale (VAS) to evaluate a participant's perception of the intensity of nausea. A mark placed on the lower part of the line or below the line would respectively indicate little or no feelings of nausea, while a mark placed higher on the line would indicate a greater amount of nausea..... 21

Figure 5. A horizontal 10-cm line was used as a VAS to evaluate participants' self-reported percent of time that dizziness interfered with daily activities..... 21

Figure 6. Wooden rocker board used for the balance tilt test (BTT). Textured squares on top of the board prevent feet from slipping. 22

Figure 7. A person positioned on the wooden rocker board during the BTT. While on the board, a participant was required to keep feet close together, eyes closed, and hands folded across the chest. During each trial, a physical therapist (not shown) stood next to the participant to provide support if a loss of balance occurred..... 23

Figure 8. The BTT was performed for a maximum of 20 seconds with eyes closed, with time recorded if a loss of balance occurred or the eyes were opened. 23

Figure 9. SVV measurements before and after off-axis rotation (OAR) for Exp. 1A (3.5 cm off-axis). Note that sessions 6 and 7 on the horizontal axis for Pre-OAR SVV represent measurements taken at 6 and 12 days following completion of OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift. 26

Figure 10. Comparison of SVV measurements before and after OAR for Exp. 1B (7.0 cm off-axis). Note that sessions 6 and 7 on the horizontal axis for Pre-OAR SVV represent measurements taken at 6 and 12 days following completion of OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift. 26

Figure 11. Difference in SVV of pre-OAR values from post-OAR values for Exp. 1A. Negative values represent a leftward shift and positive values represent a rightward shift..... 27

Figure 12. Absolute value of the difference in SVV pre-OAR values from post-OAR values demonstrating the magnitude of SVV shift for Exp. 1A. 27

Figure 13. Difference in SVV after pre-OAR values had been subtracted from post-OAR values for Exp. 1B. Negative values represent a leftward shift and positive values represent a rightward shift. 28

Figure 14. Absolute value of the difference in SVV pre-OAR values from post-OAR values demonstrating the magnitude of SVV shift for Exp. 1B..... 28

Figure 15. Exp. 1A vs. Exp. 1B: Sums of symptom intensity measured for all participants following rotation (post-OAR). 29

Introduction and Literature Survey

The vestibular system is comprised of an intricate group of organs located in the inner ear which are able to sense movement. These organs are important for the human body to maintain visual focus and overall balance. The following sections address: how the vestibular system works, vestibular dysfunction causes and symptoms, specific anatomy and mechanisms, current exercises for vestibular rehabilitation, and evidence for an innovative treatment method.

A. Role of vestibular system in human function

The vestibular system is responsible for sensing changes in head position to provide gaze stability and postural control.[1–3] Gaze stability is necessary for many daily functions, and relies on the vestibulo-ocular reflex (VOR),[4,5] which is mediated by the semicircular canals (SCC). When the head moves, the VOR causes the eyes to move with equal velocity in the direction opposite to that of head movement.[2] Nodding or shaking the head while maintaining focus on a person during a conversation is an example of this process. Postural stability relies on the vestibulospinal reflex (VSR),[4] which stimulates anti-gravity muscles to stabilize the body when head position changes.[6] The VSR requires input not only from the vestibular system, but also from the visual and proprioceptive systems.[7] For example, when a person stumbles, the VSR activates certain muscles to support the body and prevent falling. Activities of daily life, such as running, can require very fast changes in head position, yet the vestibular system is able to maintain balance by responding to changes in the vertical plane (through changes in gravitoinertial acceleration).[8] Thus, the vestibular system is important, not only to detect head movement, but also to generate appropriate motor commands to initiate responsive movement of the eyes as part of the VOR and the body as part of the VSR.[2]

B. Vestibular hypofunction

Uncompensated peripheral vestibular dysfunction can be unilateral (affecting one side) or bilateral (affecting both sides)[9] and may result in postural instability, visual blurring with head movement, and subjective complaints of dizziness and/or imbalance.[5] Such symptoms can greatly affect one's quality of life, with limitations being observed in the ability to walk, climb stairs, drive motor vehicles,[10] and maintain employment and social livelihood.[5,11,12] Persons with vestibular hypofunction are also at an increased risk of falls,[13] which can led to various injuries.

According to the National Institutes of Health, *incidence* is the number of new cases of a characteristic that develop in a given period of time; and *prevalence* is the proportion of a population who have a characteristic in a given period of time, without regard to when the characteristic was first developed.[14] Dizziness, a common complaint often associated with vestibular dysfunction, has a lifetime prevalence estimated at 17-30%.[15] Vertigo, which is the illusory sensation of motion, frequently described as spinning,[16,17] has a lifetime prevalence of approximately 3-10%.[15] A study in Germany found that dizziness/vertigo had a 1-year incidence of approximately 3% and a prevalence estimated at 23% among individuals between the ages of 18-79 years.[11] Dizziness and vertigo are most commonly diagnosed in women in general, and in both men and women of the elderly population.[11,18] Additionally, the prevalence of vestibular dysfunction is found to be higher in individuals who lack a high school education[4] and/or those living below the poverty line.[19] Possible reasons for this trend include unhealthy lifestyle habits, restricted access to medical care, and increased exposure to occupational hazards.

It has been estimated that 35.4% of US adults aged 40 years and older have balance impairment which may be linked to vestibular dysfunction.[4] Furthermore, the chance of developing balance problems increases significantly with age, with balance impairment (due to vestibular impairment and/or sensory loss in feet) affecting approximately 75% of US adults

aged 70 years and older, and more than 85% of US adults aged 80 and older.[19] According to Agrawal et al., persons with balance impairment who reported dizziness are 12 times more likely to experience falls compared to individuals with normal balance.[4]

Although dizziness, vertigo, and balance impairment often result from vestibular hypofunction, these symptoms may be caused by deficits in the central nervous or cardiovascular systems,[20] or in some cases may be linked to psychological factors.[21–23] Because of the various possible causes involved, it can be difficult for healthcare professionals to diagnose vestibular deficits,[20,24] and the diagnosis of uncompensated vestibular hypofunction often takes a long time. Some patients have waited more than a year before being referred for vestibular rehabilitation.[5,25]

Viruses (such as the herpes virus that causes chicken pox) and bacterial infections may cause damage to the vestibulocochlear nerve, resulting in vestibular neuritis or labyrinthitis.[24,26,27] Vestibular neuritis affects the body's ability to balance, while labyrinthitis affects both balance and hearing.[24] In some individuals, vestibular hypofunction is linked to Meniere's disease;[5,24,26] a condition related to increases in endolymphatic pressure that result in inappropriate nerve excitation.[7] Meniere's disease is usually accompanied with symptoms of vertigo and hearing loss.[24] Another causal factor, traumatic brain injury (TBI), results from blunt head trauma or blast exposure[28] and may be correlated with otolith damage.[29] Exposure to ototoxic medication, the most common of which is the aminoglycoside *gentamicin,* can cause damage to the sensory hair cells resulting in bilateral vestibulopathy.[30]

C. Vestibular organs involved

A vestibular labyrinth is located in each ear, and is surrounded by the very strong petrous temporal bone.[6,31] Each labyrinth contains five structures to detect head acceleration: three SCC and two otolith organs.[2] The three SCC (*anterior*, *posterior*, and *horizontal*) are located at approximate right angles to each other. These structures are responsible for sensing angular

acceleration of the head. The otolith organs consist of the saccule and utricle, and are responsible for sensation of linear acceleration and static head tilt.[7]

There is a total of six SCC, with three in the labyrinth of each ear. Each SCC contains a duct filled with endolymph, which is a fluid that moves when the head changes position. In every duct is an enlarged portion at its base, known as the ampulla. The ampulla houses the *crista ampullaris*; an elevated area of hair cells and supporting cells which is topped by a gelatinous substance known as the *cupula*.[6] The crista ampullaris and the cupula serve as a receptor system to sense the movement of endolymph fluid.[2,7] For example, when the body turns around, or spins, the endolymph fluid within the semicircular duct passes over the cupula, and signals are sent to the brain that rotational movement is occurring.[7]

Proper assessment of the VOR is necessary to evaluate function of the SCC. Caloric irrigation measures VOR function by stimulating *nystagmus*—a pattern of involuntary eye movement resulting from an asymmetric firing rate of the left and right sides—and comparing the velocity of eye movement between the left and right sides. This test applies cool water, warm water, or air to one inner ear system to stimulate that particular vestibular system and measure the resulting eye movement. The stimulus is then applied to the other side and the response is compared. The caloric test is performed while the patient reclines in a static position.[26,32,33] Function of the SCC can also be assessed through the rotary chair test, which measures eye movement velocity during rotation.[32] The video head impulse test (vHIT) is a relatively new method of examining SCC, and is useful to evaluate each of the six SCC individually, whereas caloric irrigation and rotary chair testing are used to determine function of the horizontal SCC.[32] The vHIT is performed by a clinician quickly moving the patient's head in the plane of the canal being tested, while the patient's eye movements are tracked through video-equipped goggles.[33]

Often, a combination of these tests is recommended to give the most thorough assessment of vestibular function.[32,33]

The two otolith organs, known as the saccule and utricle, send information to the body regarding linear acceleration and static head tilt.[6] Both of the otolith organs contain a *macula*, which consists of hair cells extending into a gelatinous substance known as the otolithic membrane. This membrane is covered in tiny crystals called otoconia, or *otoliths*. The word *otolith* comes from the Greek language, and literally means "ear stone".[7] These tiny stones move according to the pull of gravity.[2] The saccular macula is vertical, and its otolithic membrane moves up and down according to acceleration changes. Thus, the saccule responds best to vertical movements, such as riding in an elevator. The utricular macula, on the other hand, is horizontal, and its otolithic membrane lies on top of it. Because of this, the utricle responds best to horizontal stimuli (such acceleration while riding in a car), and also to positions of static head tilt.[6,7]

Laboratory testing of otolith organ function can be conducted by vestibular-evoked myogenic potential tests (VEMPs).[26] Cervical VEMPs (cVEMPs), use a loud sound to stimulate the saccule, while ocular VEMPs (oVEMPs) stimulate the utricle through vibration.[32,34,35] Another way to evaluate function of the otolith organs is through subjective visual vertical (SVV) testing, which evaluates function of the utricle. A static SVV test is performed with the patient sitting upright in a totally dark room, and adjusting a luminous line according to self-perception of verticality.[12,32] Results are measured in degrees away from true vertical. SVV measurements of ±2.00° from true vertical are considered within normal range, but acute onset vestibular hypofunction can result in SVV findings that are as much as 10° away from true vertical.[12]

D. Standard vestibular rehabilitation

The first vestibular therapy exercises were created and performed by Cawthorne & Cooksey in the 1940s. These researchers discovered that certain head and eye movements reduced recovery time for many patients following labyrinth surgery or head trauma.[23] Over the years, it has been found that vestibular rehabilitation plays a key role in the recovery from numerous vestibular disorders.[23] Currently, vestibular rehabilitation of peripheral vestibular hypofunction includes: gaze stability exercises, habituation exercises, gait/balance training, and general physical conditioning.[5,23,36]

Exercises to improve gaze stability involve rapid head turns that are performed while the patient maintains a target in focus.[36] Gaze stability exercises also include those that require a patient to look at a target before changing head position to face the target. The objective of these exercises is to create adaptations of smooth-pursuit eye movements or central pre-programming of eye movements to compensate for a lack of normal VOR function.[5] Habituation exercises include repeated exposure to provoking stimuli; movements that trigger dizziness and/or vertigo. Individuals are instructed to perform careful repetitions of specific movements that cause symptoms, with a goal of reducing symptom magnitude over time.[23] Additionally, optokinetic stimuli or virtual reality environments are sometimes included in habitutation therapy. Such alternative approaches may provide a stimulus through high-tech equipment, such as moving rooms or virtual reality, or provide a stimulus with lower-tech equipment, such as videos of busy environments.[5]

Gait and balance therapy involves stimulation of the visual and somatosensory systems to create compensation for absent vestibular input. Balance excercises may include movements completed while vision is distracted or removed, and/or when the patient is on an unstable surface.[23] Balance exercises also include changes in the base of support, such as a single-leg

stance, or shifting of weight from one side to the other. Gait movements involve making repeated head turns while walking in a straight line, or performing a task while walking, such as passing a ball back and forth in the hands. Computerized technology is available to create life-like scenarios for both balance and gait rehabiliation.[5,37] Examples include requiring a patient to stand on an uneven surface or walk in a straight line while surrounded by virtual stimuli of moving stripes or multicolored discs.[23] General conditioning is also recommended along with other rehabilitation measures. Walking, various aerobics, and other general forms of exercise are considered appropriate for the building of strength and endurance, which are often decreased because of a lack of movement in vestibular patients.[5]

Although vestibular therapy plays an important role in the improvement of vestibular dysfunction, rehabilitative measures are primarily aimed at the improvement of SCC-related problems. As recent studies suggest that a greater fall risk is associated with otolith dysfunction as compared to SCC dysfunction, research is needed to establish rehabilitative methods that are specifically directed toward compensation of otolith function.[38] There is a possibility that off-axis rotation (OAR), also known as centrifugation, could be linked to improvement of otolith dysfunction.[36]

E. Evidence for otolith compensation

As mentioned previously, rotation is often used for assessing function of the horizontal SCC.[32] However, during constant velocity rotation, the VOR response from the SCC is absent. The utricles, which are located approximately 3.5 cm from the midline of the head, are activated through a centrifugal force (i.e., linear acceleration) exerted on them by constant velocity rotation in a rotary chair that is at an off-axis position.[39] Additionally, it is possible that central nervous system (CNS) compensation of otolith organ function may also occur through OAR when applied to patients with utricular loss.[36]

Space flight can initiate otolith deconditioning, causing up to 75% of post-flight astronauts to exhibit symptoms such as spatial disorientation and orthostatic intolerance because of the lack of gravitoinertial force acting on the otolith organs. Buytaert and colleagues measured otolith activity in astronauts both before and after flight, and demonstrated that centrifugation during space flight may be responsible for a lack of symptoms in astronauts after returning to earth,[40] because linear acceleration creates a stimulus that is similar to the pull of gravity. Another study used SVV to measure perception of verticality before and after off-vertical-axis rotation (OVAR) in healthy subjects. It was found that SVV was significantly altered after rotation, showing "that vestibular training has an effect on perceptual responses."[17] Off-axis rotation (OAR) may likewise create changes in SVV,[39] yet the stimulus it provides is not as provocative or nauseogenic as that of OVAR.

In a recent case study, a patient who had a left vestibular neurectomy was evaluated 5 years afterward for imbalance and a "floating sensation." The patient underwent VEMP and SVV assessment, as well as balance testing. SVV measurements were recorded during constant velocity on- and off-axis rotation at 300°/s. Results indicated that the patient had uncompensated unilateral vestibular dysfunction and was referred for vestibular rehabilitation. Surprisingly, the patient soon reported a reduction in symptoms, and showed significant improvement in SVV measurement and balance results. The patient credited the improvement to OAR.[36]

F. Conclusion and Purpose

Currently, little is known in regard to treatment of patients with otolith dysfunction. It has been shown that OAR produces utricular stimulation, and that SVV is adapted in healthy individuals following rotation suggesting that the utricle has adapted to the stimulus.[36] Research also shows that patients with vestibular loss are able to experience a change in SVV over time, due to compensation from the CNS.[35] This suggests that OAR may serve as a means for

rehabilitation of otolith dysfunction, However, a review of relevant literature showed that details for stimulating otolith compensation through OAR have not yet been explored.[36]

The purpose of this study was to test different stimulus parameters on healthy controls during unilateral OAR, with the aim of determining optimal stimulus parameters to be used in the treatment of otolith dysfunction. This investigation focuses on the difference in chair position during the OAR of healthy controls. The findings here are based on SVV measurements, visual analog scale measure of symptom intensity, and balance testing.

Methods

Participants

Six healthy controls participated in OAR for the purpose of determining optimal off-axis position of the rotary chair. Participants were between the ages of 25 and 35 years (mean = 30.0; SD = 3.9) and included 4 females and 2 males. Written informed consent was obtained from each participant prior to testing. The protocol was approved by the VA/East Tennessee State University IRB Committee. Data were collected for all 6 participants during the first experiment (Exp. 1A). Data were collected for 5 participants during the second experiment (Exp. 1B) as the 6th participant completed the study later than the other participants, and the optimal off-axis distance had been determined. Inclusion criteria for the study included person of at least 18 years of age and normal vestibular function. Exclusion criteria included a history of vestibular or neurologic disorders, and/or the presence of dizziness, vertigo, or unsteadiness. Prior to inclusion, each participant underwent balance, caloric, oculomotor, and VEMP testing. Results of these tests showed normal function in all participants.

Results from SVV testing (described in Outcome Measures) were compared to a control group from a previous study. The control group included 24 healthy young controls (22 females, 2 males; mean age = 24.0 years, SD = 2.0 years).[40] Exclusion criteria included a history of

neurological disease, middle-ear pathology, open or closed head injury, cervical injury, or audio-vestibular disorder. The group underwent static SVV testing by sitting upright in a rotary chair (Micromedical System 2000) and adjusting a luminous line until it was perceived to be in a vertical position. During the first session, each member of the control group performed 5 trials of the SVV test, and an average was taken to determine mean SVV angles. The test was repeated 1-2 weeks later (second session) for the purpose of evaluating test-retest reliability (Table 1), and the absolute difference between the first and second sessions was recorded. The absolute difference mean (SD) were compared with experimental results.

Table 1. Control: group means (SD) and min/max values of SVV for Session 1 versus Session 2. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift.

	Mean (SD)	Min	Max
Session 1	0.46 (1.61)	-4	4
Session 2	1.00 (1.34)	-2	4

Equipment

The Neuro Kinetics I-Portal® NOTC (Neurotologic Test Center) rotary chair (Pittsburgh, PA) was used for OAR (Figure 1). Goggles worn by participants during OAR were the I-Portal Falcon VOG high speed video-oculography system (100 Hz frame rate), which allowed for eye movements to be tracked during each experimental session (Figure 2). A headset microphone was worn by participants in order to communicate with the chair operator during rotation. The VEST 8.0.1 software was used for operating the chair and analyzing the eye movement data.

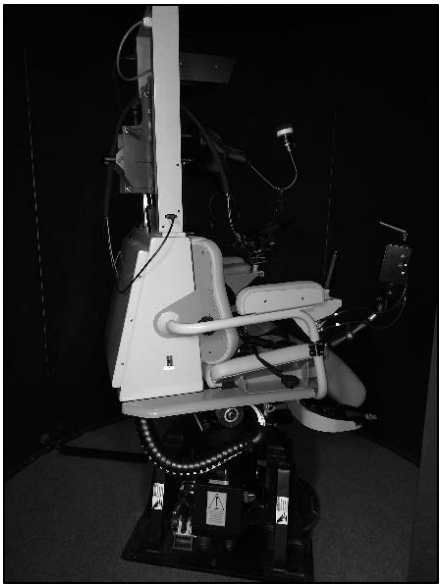

Figure 1. Side view of the Neuro Kinetics I-Portal® NOTC rotary chair, which is enclosed in a completely light-tight, darkened rotary chair booth during rotation.

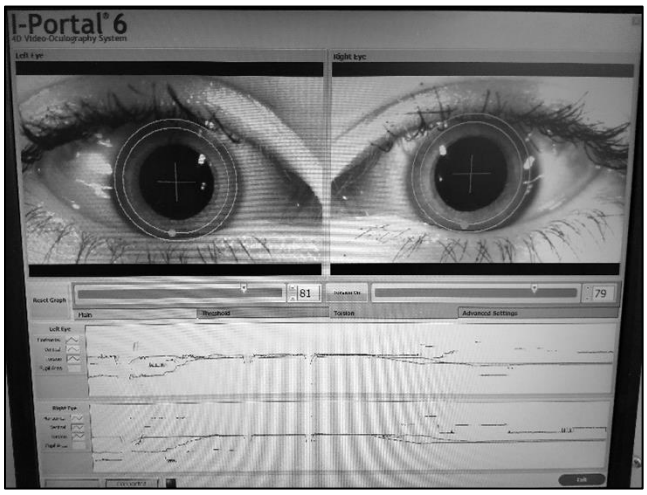

Figure 2. The I-Portal Falcon high speed video-oculography (VOG) system (100 Hz frame rate) for evaluation and recording vertical, horizontal, and torsional eye movements in collaboration with the VEST 8.0.1 operating and analysis software system.

Protocol

Each participant was placed in an upright, sitting position in the rotary chair while the chair was in a static, on-axis position. The participant's forehead, shoulders, waist, and ankles

were secured to the chair (Figure 3). Goggles and headset were secured onto the participant's head. The surrounding booth was then totally darkened to exclude any visual input except for those provided. The experiment began with a luminous red dot appearing before the participant's eyes. The participant was then instructed to visually follow the dot as it first moved up and down, then left and right, in order to allow calibration of the goggles which were responsible for tracking eye movement during OAR. SVV was then recorded (Outcome Measures) before beginning the rotation cycles.

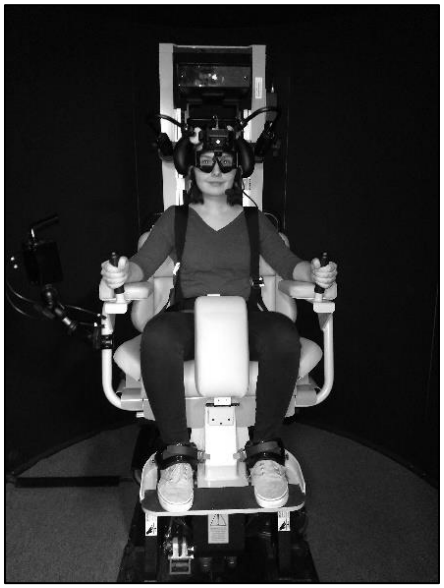

Figure 3. A person secured in the rotary chair, holding two handles with buttons to press for subjective visual vertical (SVV) adjustments. During rotation and SVV trials, the rotary chair booth was completely darkened to eliminate all visual cues other than those provided by the laser target during the experiment.

Five cycles of off-axis rotation that lasted approximately 5 minutes each were utilized for each experimental session (Table 2). Participants were either rotated to the right (clockwise direction), or to the left (counterclockwise direction), depending on the direction (left or right) that the chair was moved off-axis. Participants were always rotated in a forward-facing position toward the direction of motion, because feelings of nausea have been shown to occur as a result

of backward-facing rotation.[39] Each session required approximately 1 hour to complete, and sessions were repeated once per day for 5 consecutive days (Monday-Friday). Chair acceleration/deceleration was 5°/s^2, and chair velocity was 300°/s. All parameters were kept the same for both experiments except for the off-axis shift of the chair. Exp. 1A included a 3.5 cm off-axis shift, while Exp. 1B included a 7.0 cm off-axis shift. The two experiments were scheduled a minimum of two weeks apart, to avoid any carry-over affects following rotation. On the 6th and 12th days following completion of each experiment (1A and 1B), participants were asked to return to the lab to be to be evaluated for SVV, symptom intensity, and balance testing. Participants were not rotated on these days.

Table 2. Duration of the rotation cycle

Experiment 1A		**Experiment 1B**	
Time (s)	Action	Time (s)	Action
60	Speed up to constant velocity	60	Speed up to constant velocity
3	On-axis rotation	3	On-axis rotation
28	Shift 3.5 cm off-axis	58	Shift 7.0 cm off-axis
60	Off-axis rotation	60	Off-axis rotation
28	Return to on-axis	58	Return to on-axis
20	On-axis rotation	20	On-axis rotation
60	Slow to a stop	60	Slow to a stop
Total time = 4 min, 19s		Total time = 5 min, 19s	

Outcome Measures

Subjective Visual Vertical (SVV). Static SVV testing was conducted with a participant seated in an upright position in the rotary chair (while the chair was immobilized) and the surrounding booth completely darkened. A luminous red line appeared in front of the participant at an angle rotated away from true vertical. The participant was then asked to adjust the line with buttons under each thumb until the participant perceived the line to be in a true vertical position.

The left button caused the line to rotate to the right, and the right button caused the line to rotate to the left. Six trials of SVV were recorded. The starting angles for the line were as follows: +15°, -15°, +20°, -20°, +12°, -12°, with a negative measurement indicating that the line was rotated to the left of vertical, and a positive measurement indicating that the line was rotated to the right of vertical. Measurements within ±2.00° of true vertical were considered within normal range. SVV was measured before and after each OAR session, and at 6 and 12 days post-OAR.

Symptom Intensity. A participant's symptoms were assessed through visual analog scales (VAS). This assessment allowed participants to quantify the intensity of feelings of dizziness, nausea, disorientation, anxiety, and unsteadiness. The participant was instructed to place a mark along a 10-cm line to indicate intensity of symptoms. A mark placed at the bottom or below the line was measured as "zero" and indicated that no symptoms were experienced. A mark placed at the top of the line indicated that a maximum intensity of symptoms was felt (Figure 4). Symptom intensity was measured before and after each OAR session, and at 6 and 12 days post-OAR. In addition, the percent of time that dizziness interfered with activities (DZI) was also measured using VAS (Figure 5) and was recorded before each OAR session, and at 6 and 12 days following each experiment.

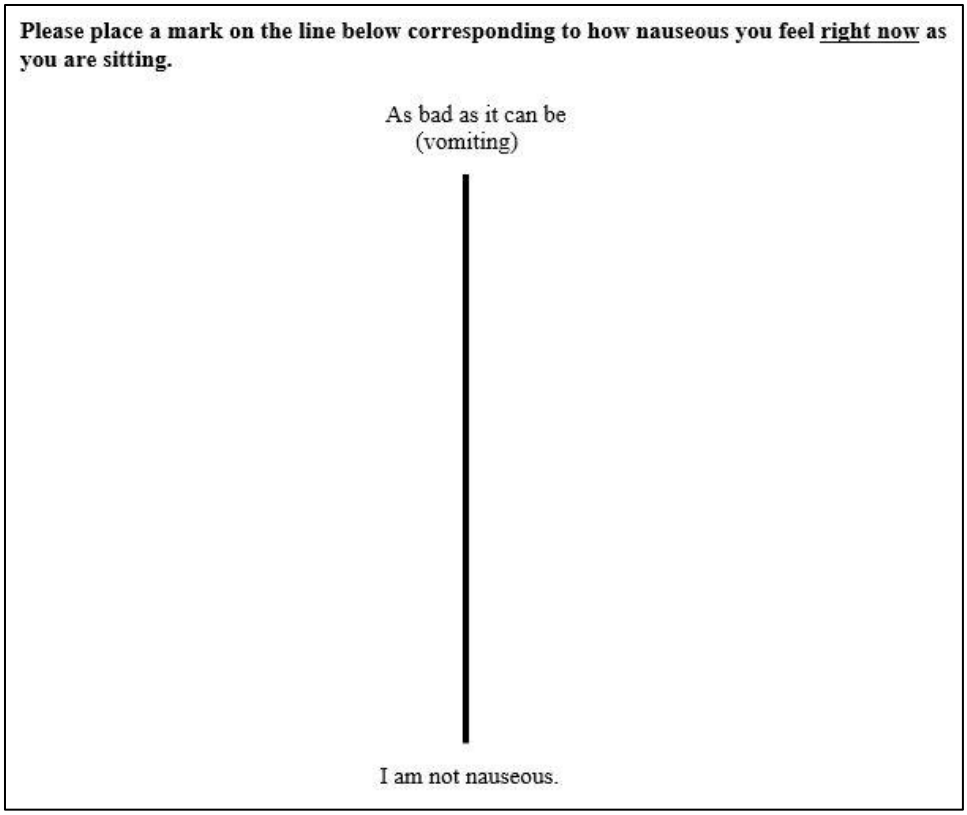

Figure 4. A vertical 10-cm line was used as a visual analog scale (VAS) to evaluate a participant's perception of the intensity of nausea. A mark placed on the lower part of the line or below the line would respectively indicate little or no feelings of nausea, while a mark placed higher on the line would indicate a greater amount of nausea.

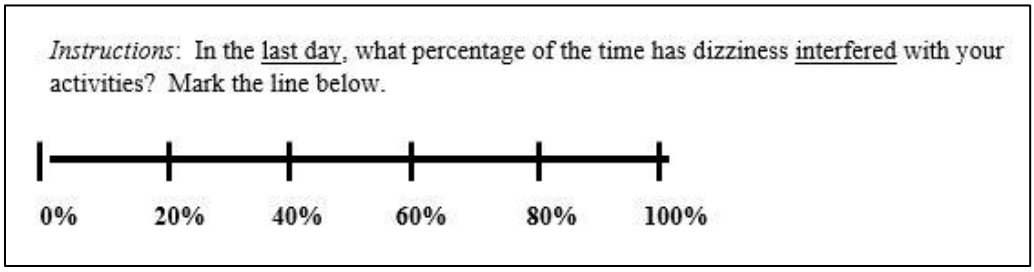

Figure 5. A horizontal 10-cm line was used as a VAS to evaluate participants' self-reported percent of time that dizziness interfered with daily activities.

Balance Tilt Test (BTT). A participant's balance ability was measured using the BTT.

Each participant was tested in bare feet standing on a wooden rocker board with eyes closed and

hands folded across the chest (Figures 6 and 7). A physical therapist stood beside the participant to provide support if a loss of balance occurred. The trial was timed for 20 seconds and resulting balance ability scored. Scores ranged from 0-3, with 0 indicating the least ability to maintain balance and 3 indicating the greatest ability to maintain balance. The test included a total of 3 trials (Figure 8), and was administered before and after each OAR session, and at 6 and 12 days post-OAR.

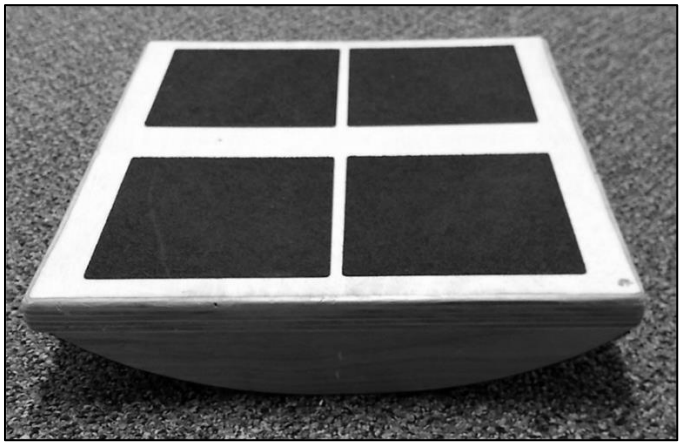

Figure 6. Wooden rocker board used for the balance tilt test (BTT). Textured squares on top of the board prevent feet from slipping.

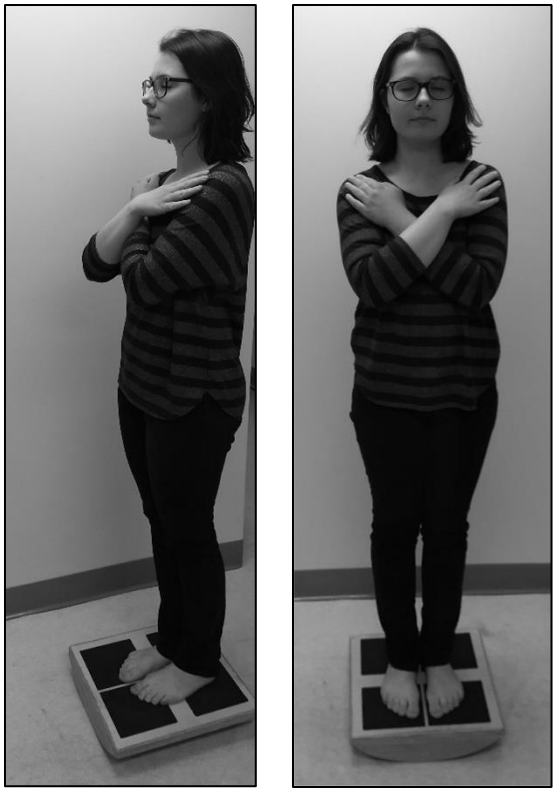

Figure 7. A person positioned on the wooden rocker board during the BTT. While on the board, a participant was required to keep feet close together, eyes closed, and hands folded across the chest. During each trial, a physical therapist (not shown) stood next to the participant to provide support if a loss of balance occurred.

Clinical Balance Tilt Test:

Trial one:

Time: _____ seconds

- ☐ 0 points = immediate fall or immediate loss of balance ('timber')
- ☐ 1 point = loss of balance but with evidence of self-righting prior to LOB
- ☐ 2 points = increase in sway to one direction, with self-righting
- ☐ 3 points = slight or no increased sway, not directionally specific

Figure 8. The BTT was performed for a maximum of 20 seconds with eyes closed, with time recorded if a loss of balance occurred or the eyes were opened.

Data Analysis

Data were summarized using descriptive statistics. To determine the effects of two distances of off-axis rotation (3.5 cm versus 7.0 cm), independent *t-tests* were performed. The difference of test-retest values (sessions repeated within 2 weeks) for a healthy control group who underwent OAR was used as the comparison for each of the 5 sessions in the current experiments. The *t-tests* compared SVV after rotation at 3.5 cm off-axis versus the control group (test-retest reliability), and 7.0 cm off-axis versus the control group (test-retest reliability). The dependent variable was the absolute value of the difference of SVV from pre- to post-OAR rotation or the absolute value of the difference of SVV between sessions 1 and 2 for the control group. A single difference measure, the average of the difference scores between sessions for the control group, was used as the comparison with OAR across sessions and for the two off-axis distances. Significance level was set at alpha = 0.05.

Results

Participants demonstrated a shift in perception of vertical as measured by SVV following OAR. Differences were observed in pre-OAR versus post-OAR measurements for each of the two experiments (Tables 3 and 4, Figures 9 and 10). These differences in SVV showed an overall leftward shift in some participants and a rightward shift in others (Figures 11 and 13). Absolute values were calculated in order to evaluate the magnitude of the shift in SVV, with results summarized in Figures 12 and 14. It is interesting to note that some participants showed magnitudes of SVV shift that were considered abnormal (greater than ±2.00° from true vertical), while others showed magnitudes that were considered normal (within ±2.00° of true vertical). This likely occurred as a result of natural variability within participants. Independent *t-tests* demonstrated a significant difference between absolute SVV differences in OAR versus the control group for the first session of Exp. 1A ($p = 0.046$) (Table 5). Symptom intensity as measured by VAS and balance as measured by the BTT were examined visually.

Table 3. Exp. 1A (3.5 cm off-axis rotation): group means (SD) and min/max values of SVV for pre- versus post-OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift.

	Pre-OAR			Post-OAR		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Session 1	-0.45 (1.46)	-2.68	1.22	-0.16 (4.18)	-7.90	3.53
Session 2	0.19 (2.10)	-2.76	2.98	1.18 (3.42)	-5.12	4.13
Session 3	-0.10 (2.02)	-2.85	2.98	-0.24 (2.68)	-5.17	2.95
Session 4	-0.45 (1.77)	-2.43	1.84	0.76 (2.91)	-5.84	2.30
Session 5	-0.08 (1.62)	-2.49	1.97	-0.68 (2.25)	-3.90	2.47
6 days post-OAR	0.10 (0.76)	-0.82	1.37			
12 days post-OAR	-0.54 (1.31)	-2.05	1.17			

Table 4. Exp. 1B SVV values: pre- versus post-OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift.

	Pre-OAR			Post-OAR		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Session 1	-0.73 (0.84)	-1.54	0.31	-1.08 (0.85)	-2.21	0.11
Session 2	-0.15 (0.28)	-0.37	0.31	-1.52 (0.99)	-3.20	-0.58
Session 3	-0.61 (0.86)	-1.60	0.62	-1.24 (1.81)	-3.73	0.21
Session 4	-0.94 (0.57)	-1.88	-0.51	-1.36 (2.08)	-3.43	1.89
Session 5	-0.57 (0.64)	-1.38	0.18	-0.94 (1.75)	-2.86	0.60
6 days post-OAR	-1.11 (1.95)	-3.82	1.70			
12 days post-OAR	-0.93 (0.84)	-1.98	0.07			

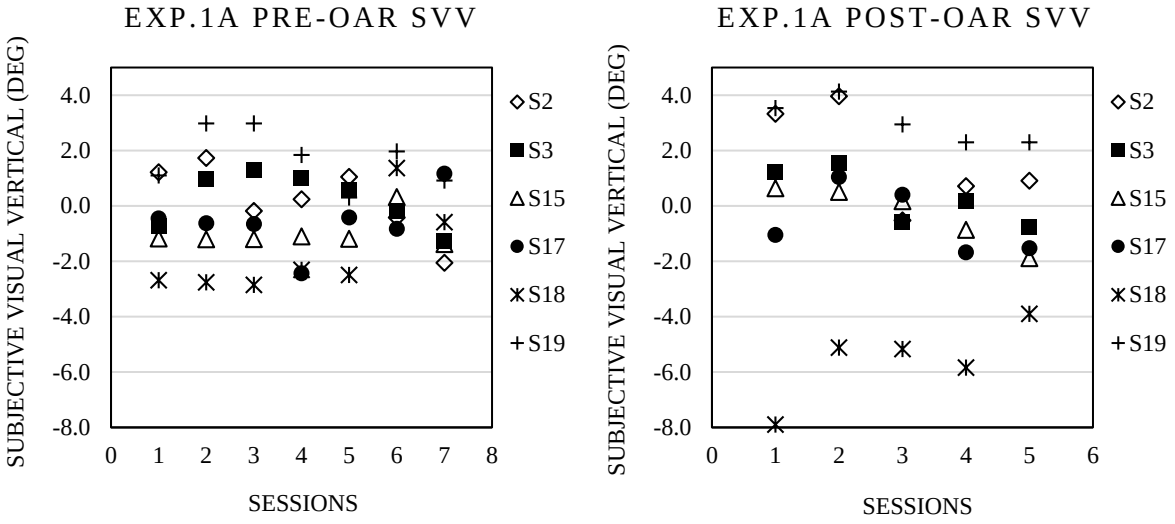

Figure 9. SVV measurements before and after off-axis rotation (OAR) for Exp. 1A (3.5 cm off-axis). Note that sessions 6 and 7 on the horizontal axis for Pre-OAR SVV represent measurements taken at 6 and 12 days following completion of OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift.

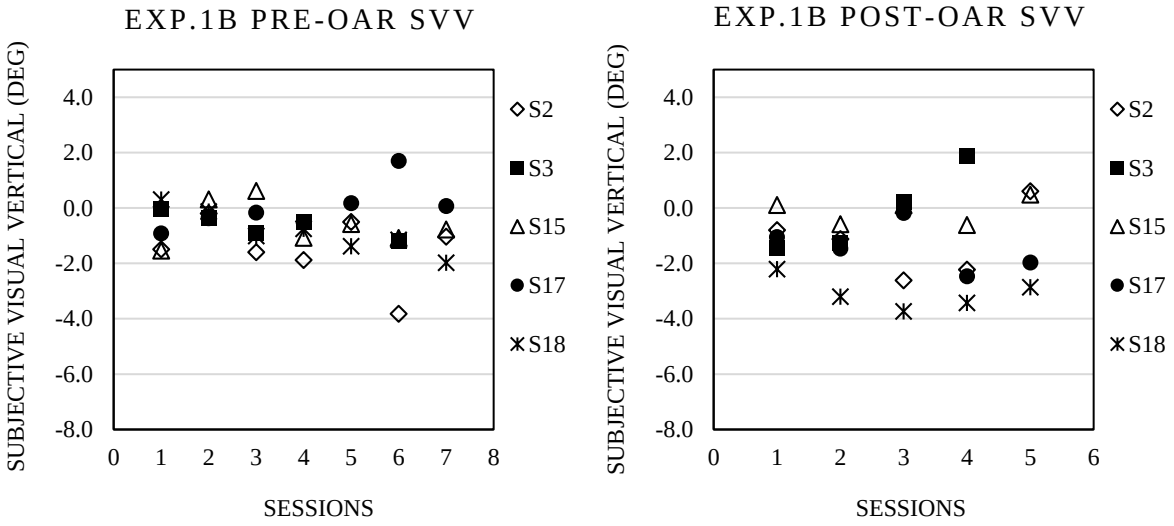

Figure 10. Comparison of SVV measurements before and after OAR for Exp. 1B (7.0 cm off-axis). Note that sessions 6 and 7 on the horizontal axis for Pre-OAR SVV represent measurements taken at 6 and 12 days following completion of OAR. Negative values represent a leftward shift from true vertical and positive values represent a rightward shift.

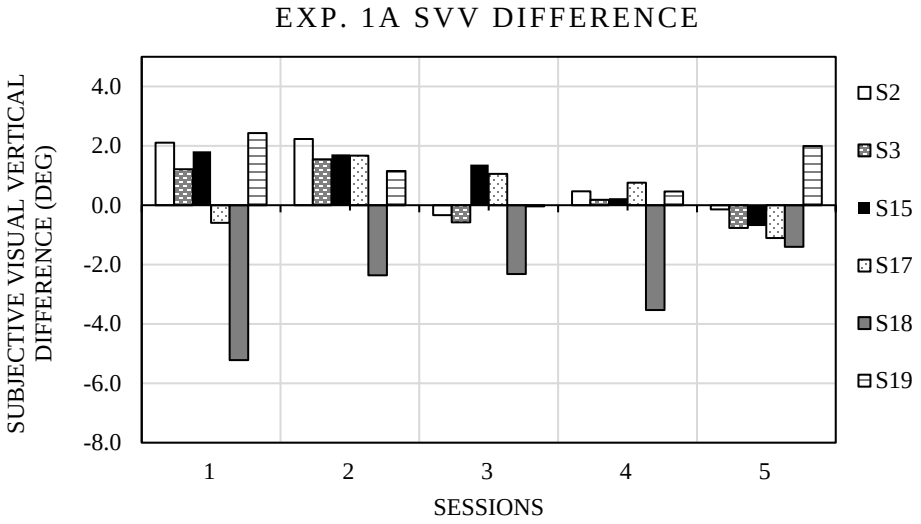

Figure 11. Difference in SVV of pre-OAR values from post-OAR values for Exp. 1A. Negative values represent a leftward shift and positive values represent a rightward shift.

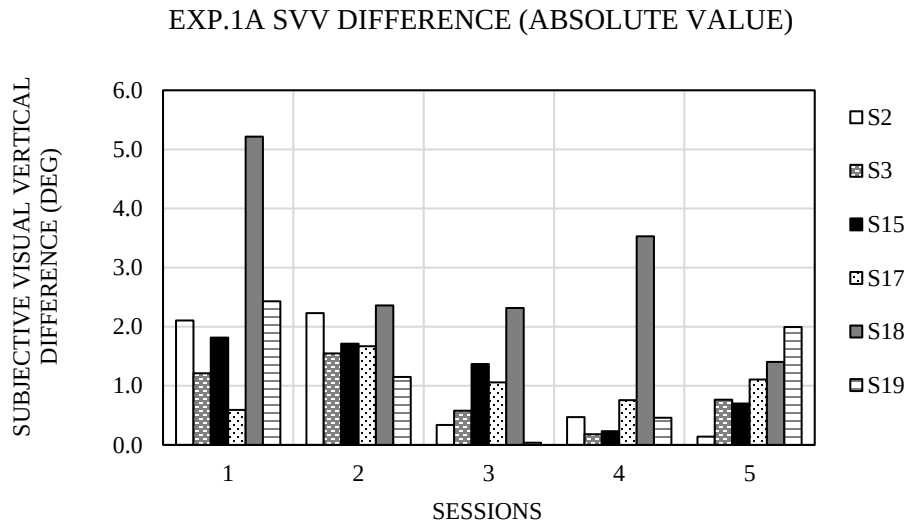

Figure 12. Absolute value of the difference in SVV pre-OAR values from post-OAR values demonstrating the magnitude of SVV shift for Exp. 1A.

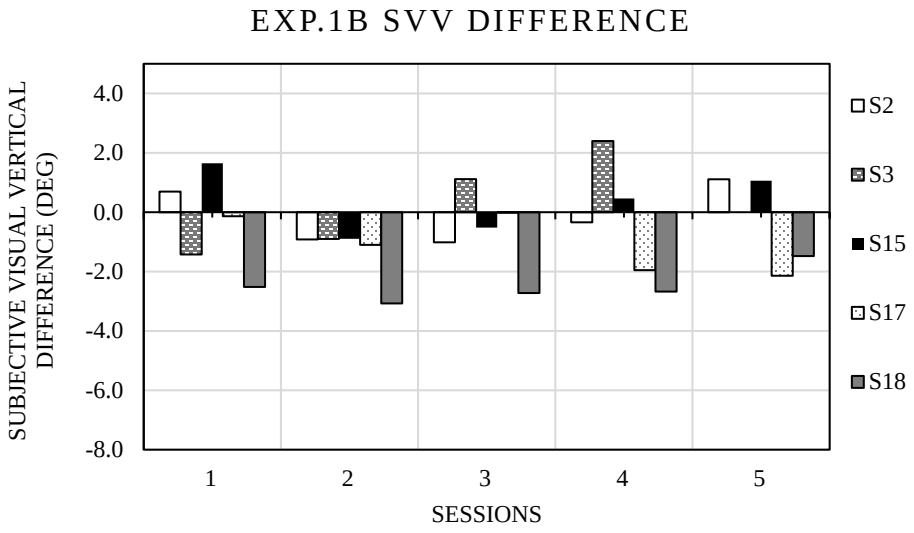

Figure 13. Difference in SVV after pre-OAR values had been subtracted from post-OAR values for Exp. 1B. Negative values represent a leftward shift and positive values represent a rightward shift.

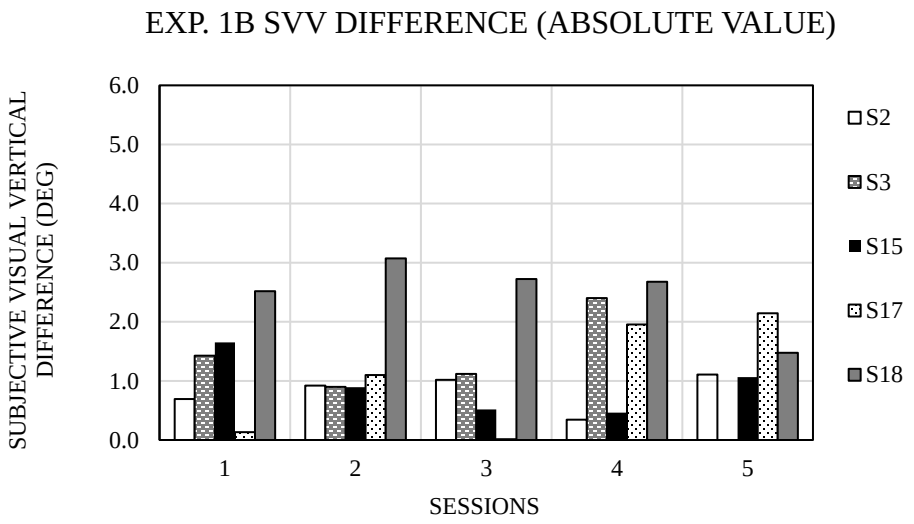

Figure 14. Absolute value of the difference in SVV pre-OAR values from post-OAR values demonstrating the magnitude of SVV shift for Exp. 1B.

Table 5. OAR versus Control: SVV absolute differences

	Control Mean (SD)	3.5 cm OAR Mean (SD)	Sig. (p-value)	7.0 cm OAR Mean (SD)	Sig. (p-value)
Session 1	1.13 (1.03)	2.23 (1.60)	0.046	1.28 (0.91)	0.753
Session 2	1.13 (1.03)	1.78 (0.45)	0.146	1.38 (0.95)	0.620
Session 3	1.13 (1.03)	0.95 (0.82)	0.703	1.08 (1.02)	0.926
Session 4	1.13 (1.03)	0.93 (1.30)	0.690	1.57 (1.09)	0.396
Session 5	1.13 (1.03)	0.77 (0.44)	0.423	1.16 (0.78)	0.947

Using values measured after rotation (post-OAR), VAS scores were collectively summed according to symptom intensity. VAS scores demonstrated differences in symptom intensity between the two experiments, with Exp. 1A (3.5 cm OAR) showing greater intensity in symptoms of nausea and anxiety. Exp. 1B, however, showed the greatest symptom intensity overall, with increased intensity in symptoms of disorientation and unsteadiness (Figure 15).

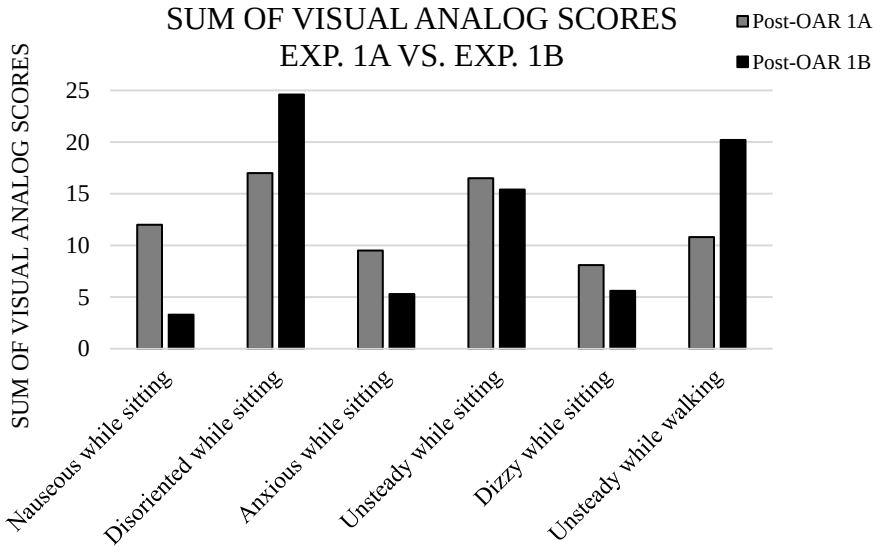

Figure 15. Exp. 1A vs. Exp. 1B: Sums of symptom intensity measured for all participants following rotation (post-OAR).

The BTT showed similar results for both Exp. 1A and Exp. 1B, with a large majority of trials recorded with a perfect score of 3 (representing the greatest ability to maintain balance). Overall balance scores were based on the sum of the 3 trials (Tables 6 and 7), thus, if a participant obtained the highest score (3) on each of the trials, the resulting total score would be 9. Similar scores were also obtained during testing on the 6th and 12th days after OAR.

Table 6. Exp. 1A comparison of BTT pre- versus post-OAR total values.

	Session 1		Session 2		Session 3		Session 4		Session 5	
	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
S2*	9	9	9	9	9	9	9	9	9	9
S3	3	3	3	3	9	9	9	9	9	9
S15	9	9	9	9	9	9	9	9	9	9
S17	9	9	9	9	9	9	9	9	9	9
S18	9	9	9	9	8	8	8	9	9	9

* S2 is a shortened form of "Subject 2." The titles listed in this column represent each of the 5 participants.

Table 7. Exp. 1B comparison of BTT pre- versus post-OAR total values.

	Session 1		Session 2		Session 3		Session 4		Session 5	
	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
S2*	9	9	9	9	9	9	9	9	9	9
S3†	9	9	9	9	9	9	9	9		
S15	9	9	9	9	9	9	9	9	9	9
S17	9	9	9	7	9	9	9	9	9	9
S18	9	9	9	9	9	9	9	9	9	9

* S2 is a shortened form of "Subject 2." The titles listed in this column represent each of the 5 participants.
† S3 was not present for Session 5.

Discussion

The results of this study provide evidence that vertical perception as measured by SVV can be altered in healthy controls through the use of off-axis rotation. Such results are noteworthy, because perception of vertical is a function of the otolith organs, and patients with otolith dysfunction have shown incorrect perceptions of vertical.[12,32,36] Because otolith

dysfunction can affect ability to move during activities of daily life, there is a need for discovery of otolith organ-specific treatment methods to help individuals who may not receive benefits from current vestibular rehabilitation exercises.

Results of several studies show that OAR may be useful in stimulating the CNS to compensate for otolith organ dysfunction. Studies involving space flight have shown that off-axis rotation stimulates otolith function, with one study applying a distance of 0.5 m off-axis (constant velocity of 254º/s), and the other applying a distance of 3.5 cm off-axis (constant velocity of 400º/s).[40,41] Carrick and colleagues researched the effects of vestibular rehabilitation methods, including OAR, on patients with PTSD (post-traumatic stress disorder) who had suffered TBIs. These researchers found that symptoms were significantly improved after treatment,[42] yet no details were included to indicate how OAR was applied. Furthermore, a recent case study showed significant improvements in otolith dysfunction following OAR of an individual with total unilateral vestibular loss. This study applied a distance of 7.0-8.0 cm off-axis (constant velocity of 300 º/s).[36]

Our investigation of healthy controls showed that a distance parameter of 3.5 cm off-axis created a shift in SVV, but that a stimulus of 7.0 cm off-axis did not produce a greater shift when applied at the same velocity. Thus, providing a stimulus of 7.0 cm off-axis was not more useful than providing a 3.5 cm stimulus for adaptation of otolith function. VAS results showed that an increase in distance off-axis was related to greater symptom intensity following OAR, meaning that the 7.0 cm off-axis stimulus produced greater discomfort in participants than did the 3.5 cm off-axis stimulus. Balance testing did not show significant differences following OAR in either of the two experiments, and thus did not provide an indication of which distance parameter was optimal.

Due to the nature of these results, we propose that 3.5 cm off-axis be used as the optimal distance parameter for OAR as a means of stimulating compensation of otolith organ function. However, limitations of our study include the small sample size, and the narrow age range of participants. It may be beneficial to repeat these study measures in healthy controls with both a larger sample size and with a broader participant age range. The findings gathered in this study may act as a starting point for future studies pursuing OAR as a treatment method for patients with otolith dysfunction.

References

1. Angelaki DE, Cullen KE. Vestibular System: The Many Facets of a Multimodal Sense. *Annu Rev Neurosci*. 2008;31(1):125-150. doi:10.1146/annurev.neuro.31.060407.125555

2. Jacobson GP, Shephard NT. *Balance Function Assessment and Management*. 2nd ed. San Diego: Plural Publishing; 2014.

3. Medendorp WP, Selen LJP. Vestibular contributions to high-level sensorimotor functions. *Neuropsychologia*. 2017;105:144-152. doi:10.1016/J.NEUROPSYCHOLOGIA.2017.02.004

4. Agrawal Y, Carey JP, Della Santina CC, Schubert MC, Minor LB. Disorders of Balance and Vestibular Function in US Adults. *Arch Intern Med*. 2009;169(10):938. doi:10.1001/archinternmed.2009.66

5. Hall CD, Herdman SJ, Whitney SL, et al. *Vestibular Rehabilitation for Peripheral Vestibular Hypofunction*. Vol 40.; 2016. doi:10.1097/NPT.0000000000000120

6. Webster DB. Vestibular System. In: *Neuroscience of Communication*. Singular Publishing Group Inc.; 1995:139-161.

7. Marieb EN, Hoehn K. Equilibrium and Orientation. In: *Human Anatomy & Physiology*. 9th ed. Boston: Pearson Education; 2013:580-588.

8. Miguel AR de, Gonzalez JCF, Macias AR. Vestibular Response to Electrical Stimulation of the Otolith Organs. Implications in the Development of A Vestibular Implant for the Improvement of the Sensation of Gravitoinertial Accelerations. *J Int Adv Otol*. 2017;13(2):154-161. doi:10.5152/iao.2017.4216

9. Brown L. What is Unilateral Vestibular Hypofunction (UVH)? *Am Phys Ther Assoc Neurol Sect*. http://www.neuropt.org/docs/vsig-english-pt-fact-sheets/unilateral-vestibular-hypofunction.pdf?sfvrsn=2. Accessed March 13, 2018.

10. Wei EX, Agrawal Y. Vestibular Dysfunction and Difficulty with Driving: Data from the 2001–2004 National Health and Nutrition Examination Surveys. *Front Neurol*. 2017;8:557. doi:10.3389/fneur.2017.00557

11. Neuhauser HK, Radtke A, von Brevern M, Lezius F, Feldmann M, Lempert T. Burden of Dizziness and Vertigo in the Community. *Arch Intern Med*. 2008;168(19):2118. doi:10.1001/archinte.168.19.2118

12. Byun JY, Hong SM, Yeo SG, Kim SH, Kim SW, Park MS. Role of subjective visual vertical test during eccentric rotation in the recovery phase of vestibular neuritis. *Auris Nasus Larynx*. 2010;37(5):565-569. doi:10.1016/j.anl.2010.02.004

13. Herdman SJ, Blatt P, Schubert MC, Tusa RJ. Falls in patients with vestibular deficits. *Am J Otol*. 2000;21(6):847-851. http://www.ncbi.nlm.nih.gov/pubmed/11078074. Accessed

March 11, 2018.

14. NIMH » What is Prevalence? https://www.nimh.nih.gov/health/statistics/what-is-prevalence.shtml. Accessed March 12, 2018.

15. Murdin L, Schilder AGM. Epidemiology of Balance Symptoms and Disorders in the Community. *Otol Neurotol*. 2015;36(3):387-392. doi:10.1097/MAO.0000000000000691

16. Vertigo | Definition of Vertigo by Merriam-Webster. https://www.merriam-webster.com/dictionary/vertigo. Accessed February 20, 2018.

17. Clement G, Deguine O, Bourg M, Pavy-LeTraon A. Effects of vestibular training on motion sickness, nystagmus, and subjective vertical. *J Vestib Res*. 2007;17(5-6):227-237. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=18626134.

18. Agrawal Y, Ward BK, Minor LB. Vestibular dysfunction: Prevalence, impact and need for targeted treatment. *J Vestib Res Equilib Orientat*. 2013;23(3):113-117. doi:10.3233/VES-130498

19. Dillon CF, Gu Q, Hoffman HJ, Ko C-W. Vision, hearing, balance, and sensory impairment in Americans aged 70 years and over: United States, 1999-2006. *NCHS Data Brief*. 2010;(31):1-8. https://www.cdc.gov/nchs/data/databriefs/db31.pdf. Accessed March 4, 2018.

20. Kerber KA, Newman-Toker DE. Misdiagnosing Dizzy Patients. *Neurol Clin*. 2015;33(3):565-575. doi:10.1016/j.ncl.2015.04.009

21. Lahmann C, Henningsen P, Dieterich M, Feuerecker R, Cyran C, Schmid G. The Munich Diagnostic and Predictor Study of Dizziness: objectives, design, and methods-IV Diagnostic and statistical manual of mental disorders, version IV SCID-I Structured clinical interview for DSM disorders. *J Neurol*. 2012;259(4):702-711. doi:10.1007/s00415-011-6250-3

22. Radziej K, Schmid G, Dinkel A, Zwergal A, Lahmann C. Psychological traumatization and adverse life events in patients with organic and functional vestibular symptoms. *J Psychosom Res*. 2015;79(2):123-129. doi:10.1016/j.jpsychores.2015.05.005

23. Han BI, Song HS, Kim JS. Vestibular rehabilitation therapy: review of indications, mechanisms, and key exercises. *J Clin Neurol*. 2011;7(4):184-196. doi:10.3988/jcn.2011.7.4.184

24. Thompson TL, Amedee R. Vertigo: a review of common peripheral and central vestibular disorders. *Ochsner J*. 2009;9(1):20-26. http://www.ncbi.nlm.nih.gov/pubmed/21603405. Accessed March 5, 2018.

25. Herdman SJ, Hall CD, Delaune W. Variables Associated With Outcome in Patients With Unilateral Vestibular Hypofunction. *Neurorehabil Neural Repair*. 2012;26(2):151-162.

doi:10.1177/1545968311407514

26. Agrawal Y, Bremova T, Kremmyda O, Strupp M. Semicircular canal, saccular and utricular function in patients with bilateral vestibulopathy: analysis based on etiology. *J Neurol*. 2013;260(3):876-883. doi:10.1007/s00415-012-6724-y

27. Ward BK, Agrawal Y, Hoffman HJ, Carey JP, Della Santina CC. Prevalence and impact of bilateral vestibular hypofunction: results from the 2008 US National Health Interview Survey. *JAMA Otolaryngol Head Neck Surg*. 2013;139(8):803-810. doi:10.1001/jamaoto.2013.3913

28. Franke LM, Walker WC, Cifu DX, Ochs AL, Lew HL. Sensorintegrative dysfunction underlying vestibular disorders after traumatic brain injury: A review. *J Rehabil Res Dev*. 2012;49(7):985. doi:10.1682/JRRD.2011.12.0250

29. Lee JD, Park MK, Lee BD, Park JY, Lee TK, Sung K-B. Otolith function in patients with head trauma. *Eur Arch Oto-Rhino-Laryngology*. 2011;268(10):1427-1430. doi:10.1007/s00405-010-1426-5

30. Strupp M, Feil K, Dieterich M, Brandt T. Bilateral vestibulopathy. In: *Handbook of Clinical Neurology*. Vol 137. ; 2016:235-240. doi:10.1016/B978-0-444-63437-5.00017-0

31. Siswanto WA, Szu Hua C. Strength analysis of human skull on high speed impact. *Int Rev Mech Eng*. 2012;6(7):1508-1514. https://www.researchgate.net/publication/235623977_Strength_analysis_of_human_skull_on_high_speed_impact. Accessed March 14, 2018.

32. Hegemann SC, Palla A. New methods for diagnosis and treatment of vestibular diseases. *F1000 Med Rep*. 2010;2:60. doi:10.3410/M2-60

33. Burston A, Mossman S, Mossman B, Weatherall M. Comparison of the video head impulse test with the caloric test in patients with sub-acute and chronic vestibular disorders. *J Clin Neurosci*. 2018;47:294-298. doi:10.1016/j.jocn.2017.10.040

34. Fife TD, Colebatch JG, Kerber KA, et al. Practice guideline: Cervical and ocular vestibular evoked myogenic potential testing. *Neurology*. 2017;89(22):2288-2296. doi:10.1212/WNL.0000000000004690

35. Schönfeld U, Clarke AH. A clinical study of the subjective visual vertical during unilateral centrifugation and static tilt. *Acta Otolaryngol*. 2011;131(10):1040-1050. doi:10.3109/00016489.2011.584902

36. Akin FW, Hall CD, Murnane OD. The role of rotational stimulation in vestibular compensation. *Otolaryngol - Head Neck Surg (United States)*. 2013;148(1):176-177. doi:10.1177/0194599812460989

37. Ricci NA, Aratani MC, Caovilla HH, Ganança FF. Effects of Vestibular Rehabilitation on Balance Control in Older People with Chronic Dizziness. *Am J Phys Med Rehabil*.

2016;95(4):256-269. doi:10.1097/PHM.0000000000000370

38. Farrell L, Rine RM. Differences in Symptoms among Adults with Canal versus Otolith Vestibular Dysfunction: A Preliminary Report. *ISRN Rehabil*. 2014;2014:1-10. doi:10.1155/2014/629049

39. Akin FW, Murnane OD, Pearson A, Byrd S, Kelly JK. Normative Data for the Subjective Visual Vertical Test during Centrifugation. *J Am Acad Audiol*. 2011;22(7):460-468. doi:10.3766/jaaa.22.7.6

40. Buytaert KI, MacDougall HG, Moore ST, et al. Validation of centrifugation as a countermeasure for otolith deconditioning during spaceflight: Preliminary data of the ESA SPIN study. *J Vestib Res Equilib Orientat*. 2013;23(1):23-31. doi:10.3233/VES-130469

41. Clarke AH, Schönfeld U. Modification of unilateral otolith responses following spaceflight. *Exp Brain Res*. 2015;233(12):3613-3624. doi:10.1007/s00221-015-4428-0

42. Carrick FR, McLellan K, Brock JB, Randall D, Oggero E. Evaluation of the effectiveness of a novel brain and vestibular rehabilitation treatment modality in PTSD patients who have suffered combat-related traumatic brain injuries. *Front Public Health*. 2015;15(3):1-8. doi: 10.3389/fpubh.2015.00015