GAZE STABILIZATION TEST:
RELIABILITY, RESPONSE STABILITY, PERFORMANCE OF HEALTHY SUBJECTS AND PATIENTS WITH CONCUSSION

by

Maha Tayseer Mohammad

B.Sc. Physical Therapy, University of Jordan, 2003

M.Sc. Physical Therapy, University of Pittsburgh, 2006

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This dissertation was presented

by

Maha Tayseer Mohammad

It was defended on

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and approved by

Patrick J. Sparto, PT PhD, Associate Professor

Gregory F. Marchetti, PT PhD, Associate Professor

Joseph M. Furman, MD PhD, Professor

Susan L. Whitney, PT, PhD, DPT, NCS, ATC, FAPTA, Associate Professor

(Dissertation Advisor)

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Abstract

Gaze stabilization test (GST) and dynamic visual acuity (DVA) test are functional measures of the vestibulo-ocular reflex which helps to maintain clear vision during head movement. The purposes of this dissertation were threefold; first the reliability of GST and DVA test were examined. Twenty-nine patients with vestibular disease were tested repeatedly using the computerized InVision™ test. Results showed that the reliability of the tests were fair to poor with the DVA reliability better than the GST and the within-session reliability better than between-session reliability.

In the second Aim, the goal was to obtain better understanding of the effect of optotype (the letter E) parameters on subjects' performance. The performance of twenty-one healthy young subjects on the GST was examined over a range of optotype sizes and presentation times. Results showed that the optotype parameters had a significant effect on subjects' performance with only one combination in which most healthy subjects were able to accomplish fast head velocities while being able to identify the optotype correctly. An optotype that is 0.30 logMAR above a subject's static vision and presented for 40 msec longer than minimum presentation time is recommended for future testing.

Lastly, the preferred combination from the second Aim was used to examine the performance of twenty-two young patients following concussion and compare it with the healthy subjects from Aim 2. Correlations between patients' performance on the GST and their scores on tests commonly used following concussion were also examined. Results showed no significant differences between the performance of patients and that of healthy subjects on the GST. Also, there were no significant correlations between the GST and other measures used following concussion.

Results show that the protocol used for the GST needed refinement. Special consideration is to be given to the optotype parameters used since these were found to significantly influence performance. The lack of significant differences between patients following concussion and healthy subjects could be due to the inclusion of all patients following concussion without objective evidence of vestibular involvement. Future studies should use specific optotype parameters and include patients following concussion with evidence of vestibular dysfunction.

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وَءَاخِرُ دَعْوَىٰهُمْ أَنِ ٱلْحَمْدُ لِلَّهِ رَبِّ ٱلْعَٰلَمِينَ

"And the last of their prayer will be: praise be to God the Lord of the worlds"

Holy Quran Chapter 10 Verse 10

Over the years, there has been a countless number of people who were there for me when I needed them, who gave me guidance when it was mostly needed, who simply stood there for me. To all of you, I want to dedicate this work to you and thank you for this treasure that you blessed me with that is your friendship… I can never mention by name everybody whom I would love to thank, but there are few names that I feel in debt to.

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1.0   INTRODUCTION

Vestibular disorders manifest with a variety of signs. These signs include dizziness and vertigo [96], disturbed balance and increased sway [92, 96], nystagmus and oscillopsia [20, 25, 108], in addition to problems with spatial information processing [12] and increased cognitive load [71, 79, 98, 111].

Visual blurring and oscillopsia are common complaints following a vestibular disorder [7, 20]. Oscillopsia is the term used to describe the illusory movement of stationary objects [14]. Visual disturbances following a vestibular disorder are the result of a dysfunction of the vestibulo-ocular reflex (VOR). The VOR helps stabilize gaze during head movement [31, 90]. Stabilization of gaze during movement is accomplished by detecting the amount of head movement and inducing eye movements of equal amount in the opposite direction to the head movement [25, 90]. The otolith organs detect translational head movements while the semicircular canals detect rotational head movements [59, 90]. Maintaining fixed eye position in relation to space (fixed gaze) during head motion insures that the images are held steady on the retina, thus maintaining clear vision during head movement.

Vestibular dysfunction that affects the vestibulo-ocular reflex (VOR) leads to deterioration of vision while walking that may lead to falling [35, 108] . Assessment of visual function, in static and dynamic situations, is important because static and dynamic visual acuity

might contribute to postural instability [44]. Tests of dynamic acuity have also been found to be reliable indicators of vestibular pathology and rehabilitative success in patients with peripheral vestibular pathologies [20, 46, 103].

The dynamic visual acuity (DVA) test compares visual acuity during head movement to static visual acuity [46, 61]. The amount of visual acuity loss during head movement provides information about the function of the VOR during dynamic situations [60]. The bedside DVA is relatively easy to apply in any clinical setting. Using a visual acuity chart, a loss of visual acuity during head movement greater than 2 lines above the static acuity has been considered indicative of a VOR abnormality [60]. The computerized DVA test provides the advantage of accurately monitoring the speed of head movement and limiting the presentation of the letter to when the required head velocity is achieved [46].

A problem with the DVA test is the use of small sized letters. The use of the test with patients with visual abnormalities is limited by the patient's vision rather than the function of the VOR [25, 77]. In addition, having the head movement fixed to certain predetermined velocities during the test limits the generalizeability of the test to different functional tasks in which different head velocities are required.

The gaze stabilization test (GST) is another method to test the function of the VOR. During the GST, the optotype size is held fixed while the speed of head movement changes [6, 25, 77, 108]. The GST is a measure of the maximum speed of head movement at which clear vision is maintained [25].

The goals of this study were to examine the reliability and response stability of the GST and to compare it with the reliability of a computerized version of the DVA test. In addition, the performance of healthy young subjects on the GST was studied using different testing

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parameters. Finally, the performance of patients following head concussion on the GST test was compared to that of healthy subjects. Patients' scores on the GST were correlated with other measures used following concussion. The measures used were the ImPACT scores (Immediate Post Concussion Assessment and Cognitive Testing, Pittsburgh, PA, USA) [62], the Dizziness Handicap Inventory (DHI) [53], and the Activities-specific Balance Confidence scale (ABC) [75].

2.0   BACKGROUND

2.1   VESTIBULO-OCULAR REFLEX

The vestibular system acts, by means of vestibulo-ocular reflex (VOR), to help stabilize vision during head movement. The ability to see clearly while moving the head depends on keeping the eyes fixed in relation to space (fixed gaze) regardless of the head movement so that images of objects are held steady on the retina [31, 90]. Degradation in visual acuity with head movement may occur due to movement of images on the retina (retinal slip). A decline of visual acuity occurs when retinal slip exceeds $2 - 4°/s$ [31]. Another possible explanation for a decline in visual acuity during head movements is the displacement of images off the fovea. In the human eyes, optimal visual acuity is at the fovea. Thus, the image of an object of interest in the visual field should be focused on the fovea [22]. Having the image off the fovea by as little as 2 degrees will cause deterioration of vision [28].

The brain uses different eye movement control systems to maintain fixed gaze during head movement. These include smooth pursuit, saccades, optokinetic, the cervico-ocular reflex in addition to the vesibulo-ocular reflex [45, 59, 92, 95]. The different systems have specific ranges in which they work efficiently.   Based on target velocity and distance plus head movement velocity and frequency, the brain decides which system to use.

The smooth pursuit system generates eye velocities at speeds < 60 deg/ sec [56, 57] that enable the tracking of slowly moving objects. The latency of the smooth pursuit system is up to 100 msec [56, 100]. Saccades quickly redirect vision to an area of interest by producing rapid eye movements (400 – 800 deg/ sec) that last <100 msec [94]. The latency of a saccade is around 200 msec [95]. The optokinetic system relies on visual input about the motion of images over the retina and supplements the VOR in the low frequency range [95]. The cervico-ocular reflex generates eye movement in response to stimulation of the neck proprioceptors [9]. In patients with vestibular dysfunction, the contribution of the cervico-ocular reflex to eye movement control is enhanced [59, 87]. The VOR works at higher speeds up to 350 deg/ sec [78] and has a latency as short as 5 msec [50, 59].

If images are not maintained on the fovea during head movement, visual blurring occurs. Head movement-induced visual blurring is termed oscillopsia [14]. Oscillopsia is an illusory sensation of movement or jumping of the surrounding stationary environment [22]. Oscillopsia indicates that the compensation for the vestibular function impairment has not occurred yet, in other words, oscillopsia is a reflection of VOR dysfunction [44]. Retinal slip, i.e. movement of the images off the fovea, manifests as oscillopsia and acts as an error signal to activate the adaptation of the VOR [42]. Another error signal that potentially activates the VOR adaptation is the position error signal [23, 85]. Position error occurs when there is a difference between the position of the gaze and the position of a target of interest during head movement [85, 90]. Preliminary evidence suggests that position error enhances VOR adaptation by increasing VOR gain [85, 90] and VOR substitution by increasing compensatory saccades [23].

Maintaining clear vision during the different activities of daily living is important for the continual and safe performance of these tasks. Visual blurring during walking or any head

movements has the potential of limiting the patients' ambulation to avoid head movements [25, 108] leading to increased dependence and isolation [43].

2.2   VOR GAIN AND PHASE

As discussed above, the VOR serves to maintain fixed gaze during head movements; this means that if the head is rotating to one side, the eyes should be moving at the same speed in the opposite direction. The function of the VOR is studied in terms of VOR gain and phase. The gain of the VOR is the ratio of eyes velocity divided by head velocity, if the VOR is functioning optimally, the VOR gain should be 1.0 or close to 1.0 [31, 59]. The VOR phase reflects the temporal difference between eye and head movements.

2.3   ANATOMY OF THE VOR

The VOR is a 3-neuron reflex-arc that connects the labyrinth with the extra-ocular muscles (Figure 1). Each semicircular canal (SCC) has excitatory connections to a specific pair of extra-ocular muscles and inhibitory connections to another pair [59, 97]. In a study by Szentagothai [97], individual SCCs were stimulated to determine which pairs of extra-ocular muscles are connected to the stimulated SCC. The superior SCC had excitatory connections with the ipsilateral superior rectus and the contra-lateral inferior oblique, while it had inhibitory connections with the ipsilateral inferior rectus and the contra-lateral superior oblique [97]. Stimulation of the posterior SCC resulted in contraction of the ipsilateral superior oblique and

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the contra-lateral inferior rectus. Stimulus to the posterior SCC also resulted in inhibition of the ipsilateral inferior oblique and the contra-lateral superior rectus. Finally, stimulation of the horizontal SCC resulted in activation of the ipsilateral medial rectus and the contralateral lateral rectus and inhibition of the ipsilateral lateral rectus and the contralateral medial rectus. Figure 2 illustrates the excitatory pathways between the SCC and the extra-ocular muscles. These connections between the SCC and the extra-ocular muscles are reflected in the patterns of nystagmus seen in patients with SCC involvement.

It is worth noting that the control of the horizontal VOR is slightly different from the control of the vertical VOR [59]. While horizontal head movements stimulate the right and left horizontal SCCs, vertical head movements activate both the superior and the posterior SCCs on the right and left side. This implies that upward head movements stimulate a different SCC than downward head movements (posterior and superior SCC, respectively). Accordingly, the neural pathways stimulated by these movements also differ [59].
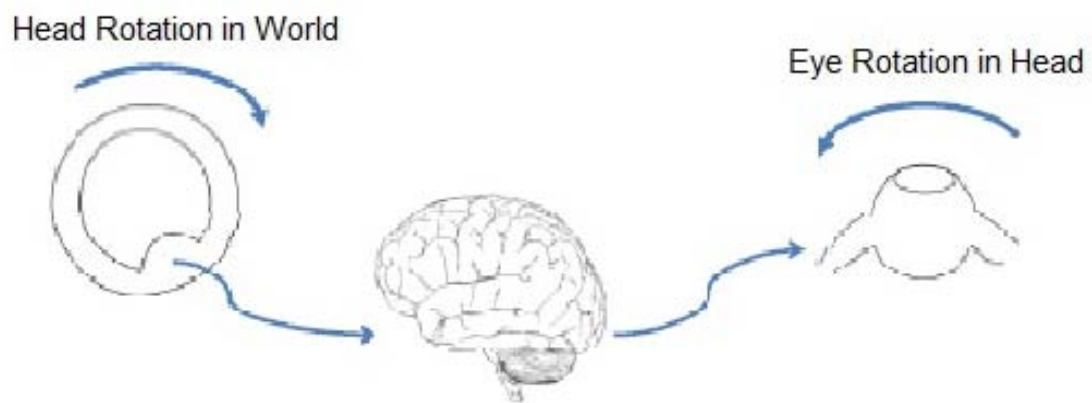
Figure 1. A simplified diagram of the vestibulo-ocular reflex
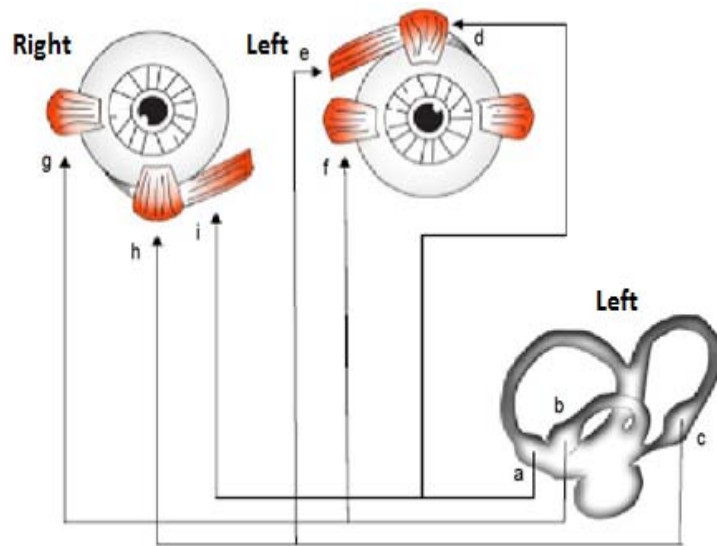
The superior SCC (a) has excitatory connections with the ipsilateral superior rectus (d) and the contralateral inferior oblique (i). The posterior SCC (c) has excitatory connections with the ipsilateral superior oblique (e) and the contralateral inferior rectus (h). The lateral SCC (b) has excitatory connections with the ipsilateral medial rectus (f) and the contralateral lateral rectus (g).

Figure 2. Excitatory connections between the three semicircular canals (SCC) and the extraocular muscles

The neurons of the VOR are located in the vestibular ganglion, the vestibular nuclei, and the ocular motor nuclei. The ampulla in each SCC sends afferents to the vestibular ganglion by means of the vestibular cranial nerve (part of CN VIII). The vestibular ganglion axons enter the brainstem to go to the vestibular nuclei which are located in the medulla and pons [10]. From the vestibular nuclei, axons travel through either the posterior longitudinal fasciculus or the substantia reticularis to the ocular motor nuclei. The posterior longitudinal fasciculus is mainly responsible for conveying excitatory stimuli, while inhibitory stimuli are conveyed through the substantia reticularis [97]. The ocular motor nuclei that receive SCC afferents are the oculomotor (CN III), trochlear (CN IV), and abducens nerves (CN VI).

There are 4 major vestibular nuclei: the medial vestibular nucleus (MVN), the lateral vestibular nucleus (LVN), the descending vestibular nucleus (DVN), and the superior vestibular nucleus (SVN) [9]. Fibers from these nuclei project to different areas of the nervous system; examples of these areas include the ocular motor nuclei, the cerebellum, descending spinal cord tracts, and the reticular formation [59].

The MVN is the largest of the vestibular nuclei [9]. The rostral portion of the MVN receives input from the SCCs and sends efferent output to the III, IV, and VI cranial nerve nuclei. The MVN plays a major role in controlling the VOR. The MVN also has connections to the cervical spinal cord and the cerebellum. The rostro-ventral portion of the LVN receives afferents from the cristae of the SCC and the macula of the utricle and sends efferent information to the occulo-motor nucleus. The LVN also sends projections to the spinal cord. The DVN sends projections to the ocular motor nuclei through its most rostral part. The SVN receives input from all SCCs. The extensive connections between the vestibular end organs and the vestibular nuclei require divergence of the data from the vestibular nerve afferents to the vestibular nuclei; a single axon from one of the SCCs activates several neurons in multiple vestibular nuclei [59].

The aforementioned connections of the vestibular nuclei from the vestibular receptors enable these nuclei to process head movement data. The vestibular nuclei also receive input from other sources which include visual, cerebellar, and proprioceptive sensory information. For example, in the vestibular nuclei several neurons that modulate the VOR receive eye movement data; these neurons include the position vestibular pause (PVP) neurons [81]. The PVP neurons receive SCC afferents about movement of the head and send efferent information to the ocular motor nuclei. Position vestibular pause neurons are active in tasks where steady fixation of

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vision on targets during head movements is required (i.e. active VOR with maximum gain). The neurons' activity is attenuated whenever the task involves a gaze shift, via saccades or smooth pursuit. The activity is more attenuated (i.e. the neurons pause) if the gaze shift is achieved by saccades. The inactivation of the VOR is required to reduce the VOR gain whenever redirection of vision from one object to another is performed during head movement [94, 95].

The activity of PVP neurons is independent of whether head movement is passive or self-generated [81]. It is proposed that efference copies of oculomotor commands sent to the PVP neurons underlie their pattern of activity. These copies can be sent from premotor circuits that generate saccades and smooth pursuit [81].

Another special type of secondary vestibular neuron is the Vestibular Only (VO) neurons which are thought to mediate the vestibulo-collic reflex [82]. These neurons are responsible for differentiating passive from active head movements. Vestibular Only neurons encode passive and not active head movements. The distinction between passive and active movement is accomplished by comparing incoming neck proprioceptive sensory information to an internal expectation of the consequences of motor commands. If sensory information matches what is expected, then movement is active and VO neurons are not activated. If there is a discrepancy, however, between what is expected and the sensory information from the neck, then the VO neurons are activated to encode passive head movement [82].

Accordingly, VO neurons activate the vestibulo-collic reflex whenever passive head movement is detected to maintain the position of the head in space. When self-generated head movement is required the VO neurons are not active since the vestibulo-collic reflex in these instances is counterproductive. The ability to differentiate between sensory information that is

the result of our own actions versus changes in the surrounding environment is critical for posture control, sensory orientation, and motor control.

2.4   VOR DURING GAIT

During gait, head movements occur at high frequencies. Dominant head perturbations during walking or running may reach up to 8 Hz [30]. The VOR is the only system capable of producing short latency responses to control eye movements. The vestibulo-ocular reflex generates eye movements at latencies of less than 5 msec [59, 95].

During walking, horizontal and vertical head velocities in normal subjects do not exceed 90 deg/ sec, and during running, horizontal and vertical head velocities do not exceed 170 deg/ sec [30]. However, these velocities of head movement were obtained during trials in which subjects were looking at a wall 7.3 meters away [30], i.e. subjects were looking straight and did not perform the horizontal and/or vertical head movements that normally accompany walking and running in different environments.

When examining the vestibulo-ocular reflex performance in normal subjects during walking and running in place while visually fixing on a target 100 meters away, Grossman et al [31] showed that peak gaze velocity was < 3.0 deg/ sec during walking (horizontally and vertically) and running (horizontally). Vertical peak gaze velocity during running ranged up to 9.3 deg/ sec. The gain of the horizontal VOR during walking and running in place ranged between 0.89 and 1.03. The gain of the vertical VOR ranged between 0.94 and 1.23. Grossman et al's work showed that the VOR was able to maintain clear vision during walking and running in

place. Pozzo et al [76] examined the control of head position during activities similar to the activities examined by Grossman (walking, walking in place, running in place, and hopping). The head velocities in the sagittal plane were always <100 deg/ sec in all tested activities.

2.5   TESTING VOR FUNCTION

Laboratory testing of the VOR function includes the caloric, the rotational chair, and ocular motor testing. The VOR parameters measured using these tests are useful to detect vestibular lesions [66]. The head thrust test is another clinical test of the VOR. One of the shortcomings of these tests is that none are functional tests. In addition, the frequencies examined in these tests are not similar to the actual frequencies during the activities of daily living during which the VOR is usually active [30].

2.5.1   Head impulse (thrust) test

The impulse test was developed by Halmagyi and Curthoys as a simple bedside clinical examination of the horizontal VOR [36]. The purpose of this test is to assess the function of the horizontal VOR in maintaining fixed gaze during rapid head movements. Small-amplitude ($\approx 5 - 20$ degrees), high-acceleration ($3,000 - 4,000$ deg/sec^2), and unexpected head thrust is applied while a subject is trying to maintain fixed gaze on a target [93]. The VOR helps maintain the eyes fixed on the target by causing slow phase eye movement that is equal in magnitude and opposite in direction to the head movement (VOR gain = 1.0). In patients with peripheral

vestibular hypofunction, the eye movement caused by the VOR is not sufficient (reduced VOR gain) and a catch-up saccade in the direction of the site of the vestibular lesion is required to bring the eyes back to the initial location [36].

In patients with unilateral vestibular hypofunction, the sensitivity of the head impulse test is 34 – 39% and the specificity is 95 – 100% [11, 37, 38]. However, these sensitivity and specificity values were calculated using the caloric test as a gold standard. The use of the caloric test as a reference is problematic, since the VOR frequencies tested in the caloric differ from those tested in the bedside impulse test. Using the scleral search coil head impulse test as a gold standard, the sensitivity of the clinical impulse test is 63 – 72% and the specificity is 64 – 78% [55]. Performing the head thrusts in the plane of the horizontal semicircular canal (i.e. with the head flexed 30 degrees) improves the sensitivity (75%) but not the specificity (82%) [93].

The timing of occurrence of the saccade relative to the head thrust influences the accuracy of the test; if the catch-up saccades occurred after the head thrust (overt saccades), the examiner can detect them and a positive diagnosis is confirmed. However, if the catch-up saccades occurred during the head thrust (covert saccades), it is impossible for the examiner to detect them leading to a false negative test result [65, 107]. The use of a scleral search coil during the head impulse test to objectively measure head and eye movement is the gold standard to detect the catch-up saccades (100% specificity and sensitivity) [55]. A new study using a light weight video occulography system attached to spectacle frames showed that the new system is as good as the gold standard in detecting the catch-up saccades [65].

2.5.2 Head shake test

During the head shake test, the subject is instructed to close his/ her eyes while the examiner applies horizontal oscillations at a rate of about 2 Hz [5, 38]. The subject is then instructed to open his/ her eyes and the therapist observes the eyes for any nystagmus. Patients with unilateral vestibular lesions manifest a nystagmus beating towards the uninvolved side [13]. Negative response (i.e. fixed gaze with no nystagmus) is observed in healthy subjects and patients with bilateral vestibular loss, the latter being due to the lack of stimulation to both vestibular systems with the head movement. Closing the eyes during this test is important since visual fixation on a target suppresses the nystagmus. An alternative to closing the eyes would be using Frenzel's goggles [13]. A 30 degree forward head flexion during the test enables examining the function of the horizontal SCC specifically [38].

The head shake test has low sensitivity (35%) and high specificity (92%) [38]. A positive head shake test is likely to indicate a vestibular lesion and has been correlated with abnormal caloric testing. However, a negative head shake test does not exclude a vestibular lesion [5, 38].

2.5.3 Caloric test

The caloric test is considered a gold standard test of vestibular function [1]. Bithermal caloric irrigation examines the function of the horizontal SCC and the superior vestibular nerve [13]. Testing is done in a darkened room using infrared goggles to record eye movement [52]. During the caloric test, warm (44° C) and cold (30° C) water is irrigated through the external auditory canal [13]. Cold water irrigation evokes horizontal nystagmus beating away from stimulated ear

while warm water irrigation causes horizontal nystagmus beating towards the stimulated ear. Asymmetrical response between the right and left labyrinthe (>25% asymmetry), reduced response (< 4 deg/ sec), and directional preponderance (> 30 %) are considered pathological findings [52]. The caloric test examines the function of the VOR at low frequencies (0.002 – 0.004 Hz) [1, 13].

2.5.4 Rotational chair test

During the rotational chair test, the subject is seated on a chair that rotates with certain frequency. Most frequencies used for the rotational chair test are between 0.01 – 0.10 Hz [1, 4]. Eye movements are recorded via electro-oculography. Nystagmus is observed during accelerating the rotary chair and when the chair movement is stopped [13]. During the acceleration phase, fast beating nystagmus is observed in the direction of rotation while slow eye movements are opposite to the direction of rotation [4]. The reverse is observed when the rotary chair is suddenly stopped [13].

The rotational chair examines the function of the horizontal SCC [1, 13]. Outcome measures of the rotational chair test include the VOR gain and phase [4, 13]. If the chair rotation was done at a frequency of 0.05 Hz, then VOR gain < 0.25 and VOR phase > 24 ° are considered abnormal findings [52].

2.6   DYNAMIC VISUAL ACUITY TESTING

The dynamic visual acuity test (DVA) compares visual acuity during active head movement and static visual acuity. In the bedside DVA test, subjects were asked to move their heads at constant speeds (at a rate between 1 – 2 Hz) while viewing a Snellen chart, the examiner reported the size of the smallest optotype (letter) subjects could correctly identify while moving their head. The frequency of head movement during the DVA test affects subject's performance; the higher the frequency, the worse the DVA test score [19]. A computerized version of the test was developed and made commercially available by NeuroCom (NeuroCom International, Inc., Clackamas, OR, USA). In the computerized version, a head mounted sensor (an InterSense Inertia Cube^2, 3-axis integrating gyro) is used to measure the range and the velocity of head movement and provide feedback to the subject and the examiner about the head movement. Other computerized versions of the DVA test are also available in the market.

Early studies of the bedside dynamic visual acuity test show that there were significant differences between DVA test scores of patients with vestibular disease and healthy age-matched subjects [60]. A drop of more than 2 lines with head movement was considered abnormal. The performance on the DVA test correlated with the degree of abnormality in the caloric test [60]. The bedside DVA test was found to be highly specific but not highly sensitive test [15]. The head movement in these early studies of the bedside DVA test was always passive. In a study examining the contribution of preprogrammed eye movements during the performance of the DVA test, unpredictable (passive) head movements caused greater decrement in the DVA than predictable (active) head movements [45].

A problem with the bedside tests of dynamic visual acuity is the lack of accurate monitoring of head movement speed. Accordingly, the optotype presentation was not coordinated with achieving the required head velocity. In addition, the contribution of eye movement control systems other than the VOR could not be excluded; the lack of accurate monitoring of the head velocity could not account for a slowing down of the head that allows for the contribution of eye control systems other than the VOR in maintaining gaze. In addition, since the bedside tests used a Snellen chart, the continuous optotype presentation during the head movement could allow the slower eye control systems to contribute to maintaining the gaze.

The computerized DVA test minimizes the use of preprogrammed eye movements by presenting the optotype at unpredictable intervals during the head movement. In addition, using a computerized test limits the optotype presentation time to an interval between $40 - 75$ msec. A short presentation interval has the advantage of excluding the contribution of eye movement control systems other than the VOR, an advantage over the bedside DVA that uses the Snellen chart. In a study examining the effect of testing position on passive DVA test scores, Danenbaum et al [18] demonstrated that testing position (sitting, standing, semi-tandem standing) did not have an effect on patients' scores on the horizontal and vertical DVA test when the head movement was performed by the therapist at a rate of 1.5 Hz.

The computerized dynamic visual acuity test has been shown to improve following vestibular physical therapy in patients with unilateral [44, 49] and bilateral [43] vestibular hypofunction. In these studies, the DVA was measured during active head movements in the yaw plane only and not in the pitch plane. In a study of the vertical DVA, Schubert et al. reported that patients with bilateral vestibular hypofunction had significantly lower scores on the vertical DVA than healthy subjects and patients with unilateral vestibular hypofunction [89].

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Roberts et al. [80] reported that the horizontal DVA was two times more sensitive than vertical DVA in detecting dysfunction of the VOR. Examining visual acuity while walking revealed that patients with a history of severe bilateral vestibular dysfunction had significant degradation in visual acuity compared to healthy controls [47].

A general problem of the DVA test is that the use of progressively smaller optotype size during the test limits its use with patients with visual comorbidities such as cataracts and diabetic retinopathy. In this patient population, the inability to see a small size optotype can be either due to a visual comorbidity or VOR dysfunction.

The velocity of head movement during the DVA test does not change while the optotype size changes. Few research labs that use the computerized version of the DVA test use a velocity range between 120 – 180 deg/ sec [6, 46]. The rationale for using this relatively high speed range is that at such high velocities the pursuit system cannot be used to control the eye movement and the VOR is the only system that can be used to maintain the stability of images on the retina [46]. In addition, a velocity of 120 deg/ sec is the upper range of head velocity during gait [30, 89].

2.7   GAZE STABILIZATION TEST

The gaze stabilization test (GST) is the most recent addition to the functional tests that objectively examine the function of the VOR. The GST measures the maximum speed at which subjects could move their head while still able to view an optotype clearly. At fast head movement velocities (> 100 deg/ sec), the VOR is the only eye control system capable of

maintaining fixed gaze and reducing retinal slip [59]. Patients with vestibular dysfunction may limit their head movement in order to maintain clear vision and reduce retinal slip [25, 108].

As discussed above, at slower head movement velocities, eye movements can be controlled by the smooth pursuit, the optokinetic system, the cervico-ocular reflex, and preprogrammed eye movements [45, 59, 92]. Since the GST measures the maximum speed a subject can achieve while still maintaining fixed gaze on an optotype of a certain size, the score on the test provides information about which activities may be limited due to the vestibulopathy, such information may prove important when following the improvement of patients with therapy. Functional performance during the activities of daily living can become limited if one's head movement is restricted to speeds below 70 deg/ sec [29-31].

In patients with vestibular hypofunction, head velocities measured using the GST significantly correlated with the patient gait performance measured using the Dynamic Gait Index and the Timed "Up and Go" test [108]. The GST cutoff values for identification of gait abnormalities were 65 deg/ sec in the pitch plane and 63 deg/ sec in the yaw plane [108]. Maximum head velocities measured using the GST test in patients with unilateral vestibular loss were reduced on the affected side and the unaffected side [25].

One of the advantages of the GST over the DVA test is the use of a fixed optotype size during the GST. The change in optotype size during the DVA test limits its use with patients with visual comorbidities. A patient's inability to see the optotype while moving the head during the DVA test can be attributed to either the visual comorbidity or the VOR dysfunction. However, in the GST, the size of the optotype used during the head movement is always large enough to account for the subject's visual comorbidity.

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Similar to the computerized DVA test, the GST minimizes the use of preprogrammed eye movements by presenting the optotype at unpredictable intervals. In addition, using a computerized test limits the optotype presentation to an interval between 40 – 75 msec. The short presentation interval has the advantage of excluding the contribution of eye movement control systems other than the VOR. A limitation of the GST is that with patients with neck musculoskeletal problems, for example older patients with arthritis, the head movement might cause pain or limit their neck mobility.

Goebel et al. [25] and Whitney et al. [108] examined the sensitivity and the specificity of earlier versions of the computerized GST. Goebel et al. reported 93% sensitivity and 64% specificity, Whitney et al. reported 44% sensitivity and 90% specificity. Goebel et al. reported a reliability index of 0.91. While Goebel et al. examined head movement in the yaw plane only; Whitney et al. examined head movement in the yaw and the pitch planes.

Ward et al [105] reported that the GST scores for young healthy subjects (age range 21 – 35) were 159.4 (34.6) deg/ sec in the yaw plane and 141.3 (26.6) deg/ sec in the pitch plane and in old healthy subjects (age range 65 – 88) 124.0 (32.5) deg/ sec in the yaw plane and 108.7 (30.2) deg/ sec in the pitch plane. In Ward et al's study, the optotype size was fixed at 0.25 LogMAR above subjects' SVA. There were significant differences in GST scores between the young and the old healthy subjects in the yaw and the pitch planes [105].

The specific aims of this dissertation were to help improve the performance of a computerized system that quantitatively measures the function of the VOR using the gaze stabilization test. The first part of this dissertation examined the reliability of the commercially available InVision™ system. Second, the size and presentation time characteristics of the optotype used for the GST were examined. In this aim, performance curves for the GST were

created. Finally, the performance of high school athletes following mild concussion on the GST was examined. Correlations of the GST scores with objective and subjective measures used in this patient population were also investigated.

3.0   SPECIFIC AIMS

3.1   SPECIFIC AIM 1

Since the InVision™ device is new technology for assessing visual/vestibular function; we first investigated the test-retest reliability and response stability of the device. In Aim 1, we determined the test-retest reliability and response stability of the InVision™ device in patients with vestibular dysfunction and correlated the patients' InVision™ test scores with their headache, dizziness, nausea, and visual blurring reported using a Visual Analog Scale (VAS).

3.2   SPECIFIC AIM 2

Contrary to what was hypothesized in Aim 1, the reliability of the InVision™ GST was poor. Accordingly, Aim 2 was adjusted to further examine the GST. In Aim 2, the optotype parameters used for the GST were examined and the algorithm used in the test was changed. The goal of this study was to examine the performance of healthy young subjects on the gaze stabilization test using different optotype size and presentation time combinations over a wide range of head velocities. Plots of performance versus head velocity were created for various

optotype size and presentation time combinations. At the end of this study we were able to decide which combination was optimal for future measurements of the GST.

3.3   SPECIFIC AIM 3

Using the optotype size/ presentation time combination obtained in Aim 2, in specific Aim 3 we examined the GST scores in young subjects following head concussion. This was a pilot study in a population in which the GST will potentially provide important information about the impact of a concussion. Our goal was to compare the performance of patients following concussion to that of healthy young subjects without concussion and to correlate the GST scores with measures used with concussion patients. The measures examined included the ImPACT scores, the DHI, and the ABC scale.

4.0 THE RELIABILITY AND RESPONSE STABILITY OF DYNAMIC TESTING OF THE VESTIBULO-OCULAR REFLEX IN PATIENTS WITH VESTIBULAR DISEASE

4.1 ABSTRACT

The purpose of the study was to investigate the test-retest reliability and response stability of the Dynamic Visual Acuity (DVA) and Gaze Stabilization Test (GST) in patients with vestibular disorders. Twenty-nine patients with vestibular disease (16 – 78 years) participated. Subjects performed the GST and DVA in pitch and yaw planes, twice in one session and once after 7 – 10 days. The GST output is the maximum head velocity at which the patient was able to identify orientation of the letter E. The DVA output is the change in visual acuity when moving the head compared to static acuity. Subjects indicated their level of dizziness and visual blurring using a visual analog scale. Within- and between-sessions intraclass correlation coefficients ranged between 0 – 0.5 for the DVA and GST measures, with better correlations for within-session assessments. Response stability (standard error of measurement / mean) of the GST ranged between 21 – 32% and the DVA ranged between 25 – 69% with vertical DVA being most influenced by measurement error. Subjects' symptoms did not correlate with performance on either test. The current test protocol needs refinement to enhance reliability and stability in persons with vestibular disorders.

4.2   INTRODUCTION

In order to maintain gaze on a stationary target while the head is moving, the vestibular system detects the velocity of the head movement and, by means of the VOR, induces eye movements that are equal in magnitude and opposite in direction to the head movements [31, 59, 90]. Maintaining fixed gaze during head movement insures that images are held steady on the retina, thus maintaining clear vision. Compared to the other systems that control the movement of the eyes, the VOR has the shortest latency (<5 msec) [59]. The function of the VOR is measured by means of the VOR gain, i.e. the ratio of the eye velocity to the head velocity. VOR gain should normally equal 1. Reduced or increased VOR gain indicates that the velocity of the eyes' movements is not equal to that of the head.

Dysfunction of the VOR leads to deterioration of vision during head movements that may lead to postural instability and increased risk of falling [35], may limit patients' ambulation to avoid falling [108], and may result in avoidance of social activities and increased dependence [43]. It is somewhat controversial as to whether vestibular dysfunction interferes with driving abilities [64]. Visual blurring indicates that compensation following a vestibular insult has not taken place yet or has been insufficient to regain normal vestibulo-ocular reflex (VOR) gain [41, 90].

The dynamic visual acuity test (DVA) [43-46, 91] and the gaze stabilization test (GST) [6, 25, 108] are two functional measures of the VOR. During DVA testing, visual acuity during head movement is compared with visual acuity with the head stationary to provide an indication about the amount of loss of visual acuity due to head movement. The DVA test was first introduced as the dynamic illegible E test [60, 61]. In the dynamic illegible E test, the subject

attempts to determine the orientation of the letter E on a visual acuity chart while the head is moved passively by the examiner at predetermined frequencies (1 or 2 Hz). The letter E was chosen because it has good legibility compared to other letters of the alphabet [60]. A computerized version of the test was later introduced in which the letters were presented on a computer screen when the head velocity reached a certain, predetermined value [46]. In the computerized version of the DVA, head movements are monitored using a velocity sensor mounted on the patient's head. The GST provides another way of examining the dynamic function of the VOR. In the GST, the maximum velocity a subject is able to achieve while still being able to correctly identify the orientation of an optotype (the letter E) presented at a specific size is measured [25, 105].

Patients with unilateral or bilateral vestibular lesions perform significantly worse on the DVA [7, 19, 43, 44, 91] and the GST [7, 25, 77, 108] when compared with healthy subjects. The performance of patients improves following a program of vestibular physical therapy which included gaze stabilization exercises [6, 8, 34, 43, 44, 49, 84]. Accordingly, the DVA test and the GST results can provide valuable information about the function of the VOR, degree of compensation, and provide a method to track changes during the physical therapy intervention.

Earlier versions of the GST and DVA test were reliable [25, 46, 77, 89]. NeuroCom International recently introduced a new computerized version of the tests; the InVision™ Tunnel System.

The purpose of the current study was to examine the test-retest reliability and the response stability of the GST and the DVA test using the computerized InVision™ Tunnel system in patients with vestibular disorders. This study also examined the influence of patients'

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perceived levels of visual blurring and dizziness symptoms on their performance on the GST and DVA tests.

4.3   METHODS

4.3.1   Subjects

Twenty-nine subjects (mean age = 50 years, SD = 14, range: 16 – 78, 5 male) with vestibular dysfunction were recruited for the study. Participants were included in the study if they were diagnosed with a vestibular disorder by a neuro-otologist. Patients were referred to the study by their treating physical therapists when the subjects demonstrated that they could tolerate the head movements required for the DVA and GST, as demonstrated by their ability to perform the VORx1 exercise without a large increase in the their symptoms. The study procedures were approved by the Institutional Review Board at the University of Pittsburgh. All participants signed the written consent before the start of the research activities. Exclusion criteria included: 1) a musculo-skeletal problem that limited neck mobility, 2) severe nausea, headache, or dizziness symptoms with head movement, 3) or static visual acuity (with corrective eye wear) worse than 20/40.

Sixteen subjects had peripheral vestibular disorders (8 right, 4 left, 2 bilateral peripheral hypofunction, and 2 with non-localized peripheral vestibular lesion), 10 subjects had central vestibular disorders (6 subjects post-concussion), and 3 subjects had mixed central and peripheral vestibular disorders. Nine of the subjects had been previously treated for benign

paroxysmal positional vertigo in addition to their vestibular pathology. Alternate binaural bithermal caloric irrigation was performed on 23 subjects; 10 subjects showed an abnormal response. Twenty five subjects were tested on rotational chair, ocular motor, and positional nystagmus tests and results were abnormal in 13, 3, and 8 subjects, respectively. Vestibular evoked myogenic potentials test was abnormal in 9 out of 21 subjects. Table 1 provides a summary of subjects' diagnoses and vestibular laboratory testing results.

4.3.2   Equipment

The InVision™ device (NeuroCom International, Inc., Clackamas, OR, USA) is composed of a CRT computer monitor that is placed inside a cabinet with a series of four mirrors that reflect the image on the screen; the subject was seated on a chair near the edge of the cabinet so that the total visual distance between the subject and the image displayed on the computer monitor was approximately 4 meters. Using testing distance of 4 meters insures that the semicircular canal system is the one being used to help maintain fixed gaze [59, 73]. Presenting visual targets close to the eyes during head movement requires the function of the otolith system to help maintain gaze in addition to conjugate eyes movements [59, 73]. Testing distance was standardized at 4 meters to better match other traditional visual assessments and testing was conducted with the subjects personal lens correction, if needed. The operator viewed a separate computer screen to control the InVision™ testing (Figure 3). A head mounted sensor (an InterSense Inertia Cube[2], 3-axis integrating gyro) was used to provide feedback about the speed and range of head movements. The head sensor had 3 degrees of freedom, an update rate of 180 Hz, and an

accuracy of 1 degree in the yaw plane and 0.4 degrees in the pitch and roll planes [51]. The head sensor is mounted on a headband that is secured around the head using an adjustable strap.

The InVision™ device was placed in a quiet room with white walls in the background. Room light was measured using a lux meter and fixed at 70 lux (per manufacturer recommendation).

Figure 3. The InVision™ test setup.

The InVision™ device (NeuroCom International, Inc., Clackamas, OR, USA). A CRT computer monitor is placed inside a cabinet (Center). Four mirrors reflect the image from the screen so that the distance between the subject and the computer screen is 4 meters. The operator views a different screen to control the test (Left monitor). A head mounted sensor (an InterSense Inertia Cube[2], 3-axis integrating gyro) provides information about the range and the speed of

4.3.3   Testing protocol

During all testing an optotype (the letter E) was presented on the computer screen. The open end of the E was pointing either up, down, right, or left and the subject was asked to determine the orientation of the E and verbally respond to the operator, who entered the response using the corresponding arrow key. The size of the E was reported in logMAR units. A logMAR is a

logarithm of minimal angle of resolution [39] and is considered the standard psychophysical unit for assessing visual acuity [40, 89]. All trials started with a short practice to ensure that subjects understood the required tasks and were comfortable performing the eye/head movements.

4.3.3.1 Static visual acuity

Testing commenced with the assessment of static visual acuity (SVA). The SVA test determined the smallest size of the optotype E the subject could see and identify correctly while the head was stationary. For this test, an outline of a black square was presented for two seconds in the center of the screen to ensure that the subject fixed his/ her vision on the location where the E would appear. After two seconds, the square disappeared, then after a 200 msec delay, the E appeared. The E remained on the screen for 2 seconds. The best Parameter Estimate by Sequential Testing (best PEST) adaptive algorithm was used to calculate the subject's SVA score. The original PEST algorithm was developed by Taylor and Creelman as an adaptive procedure to measure psychometric properties [99]. Pentland proposed a modification of the original PEST algorithm, i.e. the best PEST adaptive algorithm [72]. Compared to other algorithms, the best PEST algorithm is a more efficient procedure, requiring the fewest trials to reach a certain precision [58]. The best PEST algorithm has been used in the InVision device to determine the SVA score, in addition to determining the minimum perception time (mPT), DVA, and GST scores as will be discussed. A new SVA score was established during each testing session.

4.3.3.2 Minimum perception time

After establishing the subject's SVA, the mPT was measured. In the mPT test, the shortest duration of optotype presentation while the subject could still correctly identify the orientation of the optotype was determined. The optotype size during the mPT was fixed at 0.25 logMAR above the subject's SVA. During the mPT test a square was presented at the center of the computer screen. After two seconds the square disappeared and 200 msec later an E appeared in its place. Based on the duration of presentation of the optotype and the subject's performance, the best PEST algorithm was used to calculate the mPT score.

4.3.3.3 Dynamic visual acuity and gaze stabilization tests

The outcomes of the SVA and mPT tests were used as the baseline for the GST and DVA tests. During the GST, the size of the E was held constant at 0.25 logMAR above the subject's SVA. A value of 0.25 logMAR above SVA has been previously used in the literature. During the GST and the DVA test, the duration of the optotype presentation was calculated as follows:

- If the mPT was 40 msec or less, the optotype E was presented for 40 - 75 msec

- If the mPT was greater than 40 msec, the optotype E presentation time ranged between (mPT) and (mPT + 35) msec

According to the above criteria, an mPT score > 70 msec would lead to a presentation time >100 msec. Such long presentation time in the GST or the DVA test may allow for other eye movement systems, such as saccades, to contribute to the fixation of the eyes on the target during head movement. The InVision system flags the output in such cases as "unreliable".

The DVA and the GST required the patients to move their heads in the pitch or yaw planes while watching the computer screen. Feedback was provided to the subject and the operator via

two feedback bars that appeared on the screen before each task (Figure 4). One of the bars provided feedback regarding the range of head movement. The amount of head movement was reflected by the movement of a dot on the feedback bar. For all tasks, the subject was expected to move his/ her head approximately 20 degrees to the right, left, up, and down from the subject's neutral head position. The second feedback bar provided speed of head movement information which turned from grey to green whenever the required head velocity was achieved. Subjects were given a practice trial before each test to ensure they understood the task and the feedback provided via the two bars.

Each trial began with a presentation of the feedback bars on the screen to show the subject the required range and speed of head movement. Once the subject achieved the required speed, the bars disappeared and the subject was instructed to continue the head movement and focus his/ her vision on the square in the middle of the screen where the E appeared.

If the subject was unable to achieve the required range or velocity of head movement within 8 seconds from the start of the task or could not maintain the required speed for the minimum duration of the optotype presentation (see above), the trial was interrupted and a message appeared on the screen to indicate that the required task velocity was not achieved. The latter was considered a failed trial.

A.
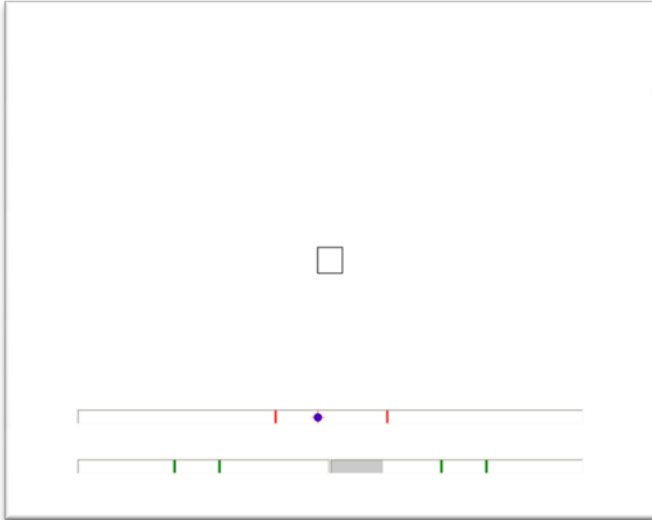
B.
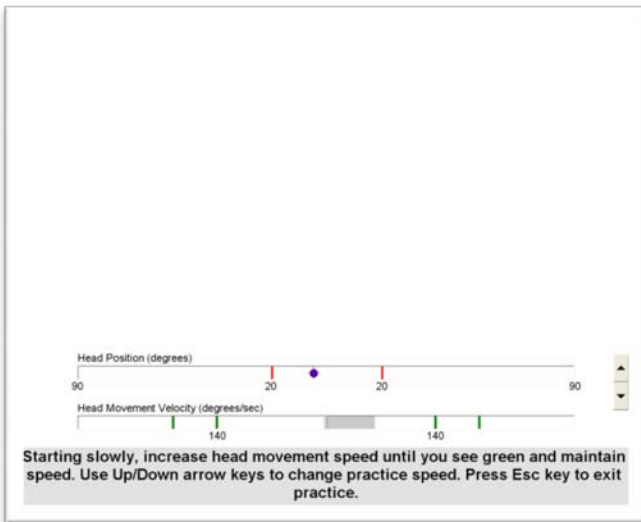
Feedback bars provided information about the head movement; the upper feedback bar reflected the range of the head motion (degrees). The lower feedback bar reflected the velocity of the head movement (degrees/ sec).

Figure 4. Screen view of (A) patient and (B) operator screen during the gaze stabilization and the dynamic visual acuity tests.

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Dynamic visual acuity test

In the DVA test, the speed of required head movement was fixed while the size of the optotype E changed. The InVision™ system (version 8.3.0) developed by NeuroCom uses a velocity range between 85 – 120 deg/ sec for the horizontal DVA test and 60 – 85 deg/ sec for the vertical direction. The maximum velocity at which the smooth pursuit system can be used is 60 deg/ sec [56, 57]. So, although the velocity we used (85 deg/ sec) is slower than the velocity chosen by the other laboratories (120 – 180 deg/ sec) [6, 34, 43, 44, 46, 89], there is no evidence that eye movement systems other than the VOR can be used at a speed of 85 deg/ sec to maintain fixed gaze. In addition, functional performance during activities of daily living can become limited if one's head movement is restricted to speeds below 70 deg/ sec [29-31]. Early trials of the DVA test using the InVision system with patients with vestibular disease showed more symptom aggravation and reduced patient tolerance at head velocities greater than 120 deg/ sec (personal communication with NeuroCom, Feb 1, 2010).

The size of the optotype in each trial varied based on the subject's responses and the best PEST adaptive algorithm until the DVA score was achieved. The DVA scores were determined for the left and right head movements during the yaw head movement test. Likewise DVA scores for up and down directions were determined during the pitch head movement test. The DVA score is the size of the smallest optotype that the subject was able to correctly identify while moving his/ her head within the predetermined speed limits. This "dynamic" visual acuity was then compared to the "static" visual acuity to determine the amount of loss in visual acuity during head movement. The DVA loss is defined as the DVA minus the SVA (DVA loss = DVA

– SVA). The DVA loss score is computed for the left, right, up, and down head movements. The outcome of the DVA test is reported as the logarithm of minimum angle of resolution (logMAR) units.

Gaze stabilization test

In the GST, the size of the optotype was fixed at 0.25 logMAR above the subject's SVA while the speed of head movements changed based on subject's performance and the best PEST algorithm. The test was stopped when the subject could no longer increase the head velocity while still being able to accurately identify the orientation of the optotype. The outcome of this test is the maximum speed at which the subject can move his/ her head while still able to identify the orientation of the E. The outcome is reported for the left, right, up, and down directions in degrees/second.

4.3.3.4 Experimental procedure

In order to establish the test-retest reliability and response stability of the InVision™ test, patients with vestibular disorders were tested twice within one session with a 30 minute rest between testing and once again 7 – 10 days later. The order of testing, i.e. DVA vs. GST, and the direction of the head movement, i.e. horizontal vs. vertical, were randomly chosen for each subject. Each repetition of the whole battery of testing was completed in 20 – 25 minutes.

Before the start of head movement testing and after each head movement task, a visual analog scale (VAS) was used to indicate the subject's level of headache, dizziness, nausea, and visual blurring [33]. For each symptom, a 10-cm vertical line marked with "no symptom at all" at the bottom of the line and "as bad as it can be" on top of the line was used. Subjects were

asked to place a mark on the line for each symptom based on how they felt [33]. In order to examine the change in subject's symptoms at any given test, their VAS score following that test was compared to the score following the immediately preceding test.

4.3.4 Statistical analysis

To determine the test-retest reliability of the measures, an intraclass correlation coefficient (ICC two-way mixed-effects model, model 3.1) [24] and 95% confidence intervals (95% CI) were calculated for the 2 within-session repetitions (the first and the second repetitions) and the between-session repetitions (the first and the third repetitions which were 7 – 10 days apart). The ICC is the ratio of between-subject variability to total variability with values ranging between 0 (no reliability) and 1.0 (perfect reliability) [74]. Values of the ICC between 0.75 and 1.0 indicate excellent reliability, values between 0.40 and 0.74 indicate fair to good reliability, while values less than 0.39 indicate poor reliability [24]. Excellent reliability (i.e. high ICC values) indicates that subject's scores are consistent over repeated measures. Intraclass correlation coefficients were calculated for subjects' scores on the SVA test, GST, DVA loss (DVA – SVA), and DVA scores.

Response stability of the GST and the DVA test was examined using the standard error of the measurement (SEM) and the SEM% for the two within-session repetitions and the first and third repetitions (between-session). Response stability is a measure of the consistency of repeated responses over time [74]. The SEM is an estimate of the within-subject variability (standard deviation of an individual's score) after repeated measures. The SEM was calculated using the sample standard deviation (SD) and the ICC as follows: $SEM = SD \sqrt{(1 - ICC)}$. The

SEM% provides a standardization of the SEM to enable the comparison of measurement error across different tests. The SEM% equals SEM/ mean * 100%. Using the SEM, the minimal detectable change (MDC) was calculated for those tests with ICC values that are significantly different from 0. The MDC is the amount of change in the measure that is greater than chance or measurement error [54]. The MDC is an important measure when examining the change in subjects' performance after repeated measurements on a test. The 95% MDC = SEM * 1.96 * $\sqrt{2}$.

Correlational analysis between the GST and the SVA was performed using Pearson product moment correlation (PPMC). The goal was to examine whether high SVA scores (larger optotypes) correlated with faster GST scores. The correlation between the GST and the DVA test was calculated to examine the relationship between the two tests. In order to examine the change in subjects' dizziness and visual blurring after each head movement testing, repeated-measures t-tests were calculated on subjects' VAS scores before and after each test. In order to examine whether subjects' symptoms were associated with their performance on the GST or DVA test, correlational analysis between the GST or DVA loss scores and subjects' symptoms was performed using Spearman non-parametric correlations. Spearman correlations were chosen due to the non-normal distribution of the VAS which was used to report the subjects' symptoms. Due to the multiple comparisons performed in the correlational analyses, alpha levels (α) were set at 0.01. All analyses were performed using SPSS (version 17, SPSS Inc., Chicago, IL.)

4.4   RESULTS

Table 2 shows the mean (SD) scores for subjects over the 3 repetitions of testing on the SVA, GST, DVA loss, and DVA. The GST and DVA scores are shown for left/right and up/down directions. Of the 29 subjects who participated in the study, 24 subjects returned for the second visit in which the third repetition of testing was performed. One of the subjects who returned for the second visit did not repeat the DVA for the 3rd repetition due to limited session time (i.e. n for DVA on 3rd repetition = 23) but the subject did complete the GST. The overall mean of the SVA scores was -0.04 ± 0.12 logMAR.

On the mPT test, one subject who came for one session of testing only scored 90 msec on one repetition of the mPT. As discussed earlier, an mPT score of 90 msec leads to an optotype presentation range during the GST and DVA test between 90 – 125 msec. Such an extended presentation time renders the GST and DVA test invalid since the contribution of eye movement systems other than the VOR to the fixation of the eyes during the head movement could not be excluded. This subject's scores were excluded from the analyses. With that subject excluded, the mPT scores ranged between 20 and 50 msec in increments of 10 msec. The median of the mPT score was 20 msec.

On average, patients' scores ranged between 124 – 152 deg/ sec on the GST and 0.16 – 0.25 logMAR on the DVA loss test. On the DVA loss test, patients' scores in the yaw plane were worse than in the pitch plane, perhaps due to the higher head velocity in the yaw plane (85 – 120 deg/ sec) compared to the pitch plane (60 – 85 deg/ sec); the difference was not statistically significant. There were no significant differences between patient's performance on the left and right directions or between up and down directions in the GST and DVA test.

Test-retest reliability was examined using the ICC (model 3.1). The reliability was examined within-session (using the first and the second repetitions) and between-session (using the first and the third repetitions). Test-retest reliability for the SVA was excellent for the within-session repetitions (ICC = 0.89, 95% CI: 0.78 – 0.95) and between-session repetitions (ICC = 0.85, 95% CI: 0.68 – 0.93).

Estimates of the reliability of the GST and the DVA test were higher within-session than between-session (Table 3). The reliability of the GST was generally poor (ICC values between 0 and 0.48). Estimates of the GST reliability in the horizontal direction (ICC: 0 – 0.48) were slightly better than the vertical direction (ICC: 0 – 0.35). In the DVA test, the reliability of the DVA loss was poor to fair in all four directions (ICC: 0 – 0.50). However, when DVA scores were examined, the ICC values were good to excellent (ICC: 0.64 – 0.79) (Table 3).

For the GST, the number of subjects used to calculate the reliability estimates varied in each direction tested (Table 3). Using the best PEST algorithm, if the subject was unable to perform the GST in one direction after the first few trials, even at very slow speed, testing for that direction was stopped and the subject was assigned a "No Score" for that direction.

The response stability of the GST and DVA loss tests was examined using the SEM and SEM%. Table 4 shows the SEM and SEM% values for the GST and DVA loss test. The SEM% for the GST ranged between 21 – 32% and for the DVA loss between 25 – 69%. The vertical DVA test appeared to be the most influenced by measurement error (SEM%: 44 – 69%).

The GST and DVA scores of the 12 patients with a unilateral peripheral lesion (8 right and 4 left lesions) in terms of lesion vs. non-lesion sides are displayed in Table 5. There were no significant differences toward the lesion and non-lesion sides. There were no significant correlations between subjects' scores on the GST and their SVA scores (R < 0.40) (Table 6). The

lack of significant correlation between GST and SVA indicated that, within the parameters used in the current test, patients' performance on the GST was not influenced by the size of the optotype presented during the test. The correlations between the GST and the DVA test were examined. The correlations were expected to be somewhat strong to reflect that the two tests measure two constructs that are similar (the function of the VOR) but not identical. In general, the GST and the DVA loss were inversely correlated. Higher GST scores (i.e. faster head velocities) were correlated with lower DVA loss scores (i.e. reduced loss of visual acuity with head movement). Most of the correlations (8 out of 12) were weak ($R < 0.38$, Table 7). However, 4 of the 12 correlations were strong (R: $0.52 - 0.72$). The correlations seemed to be slightly stronger in the yaw plane (left and right) compared to the pitch plane (down and up).

Patients were asked to report their symptoms of nausea, headache, dizziness, and visual blurring on a 10-cm VAS before and after each test. Most patients did not report any nausea or headache symptoms during testing. On average, patients' level of dizziness before testing was 3.7 cm out of 10.0 cm. The average increase in dizziness after testing was 1.5 cm (SD = 2.3). The level of visual blurring before testing was 2.6 / 10.0 cm and the average increase in the symptom after testing was 0.6 cm (SD = 1.5). Over the 3 repetitions of testing, patients were asked about their symptoms 12 times (3 repetitions of 2 tests (GST and DVA) with 2 directions in each test (horizontal and vertical)). The change in dizziness was statistically significant 6 out of the 12 times. The change in visual blurring was statistically significant only once; after the 3rd repetition of the vertical GST. None of the correlations between patients' scores on the GST or the DVA loss test and their dizziness or visual blurring symptoms were significant.

4.5   DISCUSSION

The reliability of the NeuroCom InVision™ GST and DVA test in patients with vestibular disorders is poor to fair. Overall, the reliability of the tests was better within-session than between-session with the reliability of the DVA test better than that of the GST. To our knowledge, no other study has examined the reliability of the DVA or the GST between-session in persons with vestibular disorders; all reliability studies available in the literature repeated testing in one session on the same day [25, 46, 89].

The DVA loss is defined as DVA – SVA. Although the DVA scores were reliable (ICC between 0.65 and 0.79) and the SVA test was also reliable (ICC between 0.84 and 0.89), the DVA loss scores were not as reliable (ICC between 0.11 and 0.50). The drop in reliability raises the question that maybe the patient's SVA scores should be established at the beginning of the intervention and the same SVA scores should be used for all follow up DVA tests. The standardization of the test procedure could increase the reliability of the test and ensure that any changes in the DVA loss scores are attributed to the changes in DVA and not SVA scores. The method described in the available literature that examined the reliability of the DVA loss test suggests that the SVA test was not repeated and only the DVA test was repeated [46, 89].

In a previous GST study, the reliability of the NeuroCom InVision™ system was examined in healthy young (25 ± 3 years) and older (76 ± 5 years) subjects [105]. The device was found to be reliable for both the GST (ICC values between 0.54 – 0.75) and the DVA test (ICC values between 0.10 and 0.60)[105]. In the study of healthy subjects, right and left test scores were averaged into a single yaw plane score. Similarly, up and down scores were averaged into a single pitch plane score. The statistical analyses in the current study were

conducted differently since the nature of the patients' vestibular diseases renders the unidirectional performance asymmetrical, thus averaging the scores was not plausible in the patient population. However, when patients' scores in the yaw plane were averaged, the reliability values did not improve; the reliability within-session was 0.44 and between-session 0.09. It appears that the low reliability in the current study was not due to the different statistical methods used.

Herdman et al [46] examined the reliability of an earlier version of the computerized DVA test in the horizontal direction while Schubert et al [89] examined the vertical direction. Their results indicate that the computerized DVA test was reliable when used with patients with vestibular deficits (ICC = 0.83 for horizontal and 0.94 for vertical DVA). Several differences exist between the current study and the ones conducted by Herdman et al. and Schubert et al. that render the comparison between the studies difficult. First, as discussed above, when examining the reliability of the DVA test, only the dynamic component of the test was repeated and not the SVA test. Second, testing distance in our study was fixed at 4 meters; the other two studies used a testing distance of 2 m. We chose 4 m to better match other traditional visual assessments. In addition, the head velocity used for the DVA test in the Herdman et al. and Schubert et al. studies was 120 – 180 deg/ sec for both horizontal and vertical DVA. In our study, we used a slower velocity range (80 – 120 deg/ sec for horizontal and 60 – 85 deg/ sec for vertical). Finally, while the InVision system uses the best PEST algorithm to calculate the final DVA score, the algorithm used by Herdman et al and Schubert et al always used 5 presentations of the optotype (the letter E) at each acuity level; such an algorithm can be time consuming and may trigger patients' symptoms, especially when considering that the DVA test is done for right, left, up, and down directions. One of the advantages of the best PEST adaptive algorithm is that it uses fewer

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trials to calculate the final score but the increased efficiency may come at a cost of reduced reliability.

Schubert et al [89, 90] reported that when examining visual acuity of their subjects, testing was stopped when a subject scored 0 logMAR on the SVA or the DVA. A score of 0 logMAR corresponds to 20/20 vision on the standard Snellen chart. In our experience, subjects, especially those with corrected vision, can score below 0 on visual acuity testing, especially the SVA. For example, in the current study, 19 out of the 28 patients had an SVA score below 0 logMAR. Stopping testing at 0 logMAR means that the DVA loss score will not reflect the real difference between subjects' DVA and SVA scores but the difference between their DVA score and 0. Assessing reliability of DVA loss when using a lower limit of 0 for SVA would be similar to assessing reliability for DVA (not DVA loss). Our study found that reliability for DVA was higher than that for DVA loss and more similar to the findings of Schubert et al.

When examining the DVA test or the GST in the vertical direction, it is important to document if the patient is wearing bifocal glasses. During the testing of the downward direction, the optotype is presented shortly after the subject starts moving downward after reaching the maximum upward excursion; thus the optotype may be presented while the patient is looking through the lower half of the lens which is typically used for reading. Since the optotype is presented at a distance of 4 meters, the subjects' inability to identify the orientation of the optotype may be due to the inappropriate correction rather than a VOR deficiency. The DVA test would be expected to reflect this problem more than the GST since the size of the optotype in the GST is held constant above the subject's SVA. Eight patients were tested while wearing bifocals; the mean score on the DVA loss test for the bifocal wearers in the down direction was 0.16

logMAR vs. 0.13 logMAR in the up direction. On the GST, the mean score of the bifocal wearers was 148 deg/ sec for both up and down directions.

Goebel et al [25] examined the reliability of the GST in the horizontal direction only on an earlier version of the InVision™ system. The ICC for the GST in the horizontal direction was 0.91. The optotype used by Goebel et al was 0.30 logMAR above the subjects' SVA and the testing distance was 3 meters. In the current study the optotype size was 0.25 logMAR above SVA at a 4-meter distance. Goebel et al [25] used larger optotypes at a shorter testing distance. In our clinical experience, such a seemingly minor change in optotype increment and testing distance could significantly affect the patients' performance on the test, rendering the comparison between the results of the two studies difficult.

Ward et al. [105] calculated the MDC for the GST and DVA loss test using a sample of healthy subjects. The MDC for the GST was 51 – 55 deg/ sec and for the DVA loss test 0.14 – 0.24 logMAR. The MDC values for the GST in the current study are larger than those of Ward et al. The difference is mainly due to the larger ICC value for the horizontal GST in the sample of healthy subjects (ICC = 0.69). A possible explanation for the larger MDC value in patients is that there was greater variability in the patients' performance.

The correlation between the GST and the SVA was examined to investigate whether higher SVA scores were correlated with better/ faster GST scores. Higher SVA scores mean that larger optotypes would be presented during the GST. We wanted to confirm that the larger optotypes did not make the GST easier for subjects with poor vision simply due to the size of the optotype used. There were no significant correlations between the GST and the SVA suggesting that the larger optotypes used did not affect the findings.

The DVA test is widely used to functionally examine the VOR in patients with vestibular disorders. The GST is a relatively new test. The correlations between the GST and the DVA tests were generally weak, suggesting that the GST and the DVA tests may measure different aspects of the function of the VOR.

Several studies have examined the correlation between patients' symptoms during testing, specifically visual blurring, and their GST or DVA scores [7, 43, 44, 89]. Our results were consistent with previous findings; there were no significant correlations between patients' symptoms and their functional VOR test results. The only study that found a significant correlation between DVA (specifically in the up direction) and visual blurring used a passive DVA test and had more stringent inclusion criteria (>50% asymmetry on the Caloric test compared to >25% asymmetry in other studies) [7]. The lack of significant correlation between the GST and DVA test and the patients' symptoms may be because symptom provocation and the GST/DVA tests may measure different constructs.

The algorithm used for the GST appears to need further refinement. While most available studies in the literature used an algorithm where the optotype was presented five times at each head velocity and testing advanced in increments of 10 deg/ sec [25, 77, 108], the InVision system used in the current study utilized the best PEST adaptive algorithm to control the progress of the test and calculate final GST scores. The earlier algorithm is time consuming and may provoke patients' symptoms, especially when considering that testing is usually done for the right, left, up, and down directions. At the same time, while the best PEST algorithm uses fewer trials to calculate patients' scores, its use may not be optimal for the GST but appears to be acceptable for the DVA.

4.6   CONCLUSION

Future research will be aimed at improving reliability and stability of DVA testing and of the GST. To accomplish this, the best PEST algorithm may need to be replaced with an algorithm that can be tailored for each patient. The GST and DVA tests provide valuable information about the functional performance of the VOR. If the SVA used for the DVA test is standardized, the InVision system's DVA test appears to have good reliability. As for the GST test, the current protocol needs to be altered to improve the reliability of the test scores and the ease of comparison across different laboratories. Testing distance, size and presentation time of the optotype, and the testing protocol should all be examined further in an attempt to enhance the reliability of the GST in persons with vestibular dysfunction.

Table 1. Patient diagnoses and vestibular laboratory testing results

Patient Diagnoses		N (%)
Peripheral vestibular disorders		16 (55%)
	Right	8
	Left	4
	Bilateral	2
	Non-localized	2
Central vestibular disorders		10 (35%)
	Post –concussion	6
Mixed central and peripheral vestibular disorders		3 (10%)
Vestibular disorder plus BPPV		9 (31%)
Vestibular Laboratory Testing		
Caloric test (n = 23)		10
Rotational chair (n = 25)		13
Ocular motor (n = 25)		3
Positional (n = 25)		8
Vestibular evoked myogenic potential (n = 21)		9

Table 2. Mean and standard deviation of static visual acuity (SVA), gaze stabilization test (GST/ left, right, up, and down), dynamic visual acuity loss (DVA loss/ left, right, up, and down), and DVA (left, right, up, and down) for all 3 repetitions of testing in patients with vestibular disease.

	Session 1		Session 2
	1st repetition	2nd repetition	3rd repetition
SVA (logMAR)	-0.03 (0.11)	-0.04 (0.13)	-0.06 (0.14)
GST (deg/sec)			
Left	130 (48)	139 (50)	152 (39)
Right	136 (38)	143 (50)	143 (42)
Up	131 (45)	138 (42)	124 (37)
Down	138 (35)	142 (37)	128 (36)
DVA loss (DVA – SVA) (logMAR)			
Left	0.24 (0.09)	0.20 (0.12)	0.19 (0.10)
Right	0.25 (0.09)	0.18 (0.12)	0.18 (0.10)
Up	0.16 (0.12)	0.18 (0.11)	0.17 (0.09)
Down	0.16 (0.10)	0.16 (0.11)	0.17 (0.09)
DVA (logMAR)			
Left	0.21 (0.14)	0.17 (0.13)	0.12 (0.13)
Right	0.22 (0.14)	0.14 (0.16)	012 (0.17)
Up	0.12 (0.18)	0.15 (0.17)	0.10 (0.17)
Down	0.12 (0.15)	0.12 (0.16)	0.10 (0.15)

DVA loss = DVA – SVA.

Table 3. Intraclass correlation coefficient (ICC) with 95% confidence intervals for the SVA, GST, DVA loss, and DVA in the left, right, up, and down directions within-session (1st and 2nd repetitions) and between-session (1st and 3rd repetitions).

	Test (direction)	Within-session	Between-session
SVA		0.89 (n = 29, CI: 0.78 – 0.95)	0.85 (n = 24 , 0.68 – 0.93)
GST	Left	0.48 (n = 27, CI: 0.13 – 0.72)	0† (n = 24)
	Right	0.38 (n = 28, CI: 0.01 – 0.66)	0.25† (n = 24)
	Up	0.25† (n = 26)	0.35† (n = 21)
	Down	0.29† (n = 27)	0† (n = 23)
DVA loss	Left	0.50 (n = 28, CI: 0.16 – 0.73)	0.10† (n = 23)
	Right	0.22† (n = 28)	0.50 (n = 23, CI: 0.12 – 0.75)
	Up	0.26 † (n = 28)	0† (n = 23)
	Down	0.47 (n = 28, CI: 0.13 – 0.72)	0.23† (n = 23)
DVA	Left	0.79 (n = 28, CI: 0.59 – 0.90)	0.76 (n = 23, CI: 0.52 – 0.89)
	Right	0.65 (n = 28, CI: 0.37 – 0.82)	0.79 (n = 23, CI: 0573 – 0.91)
	Up	0.77 (n = 28,CI: 0.56 – 0.88)	0.64 (n = 23, CI: 0.32 – 0.83)
	Down	0.77 (n = 28, CI: 0.56 – 0.89)	0.79 (n = 23, CI: 0.56 – 0.90)

† ICC value not statistically different from ICC = 0 ($\alpha = 0.05$, Analysis of Variance F-test)

GST = gaze stabilization test (deg/ sec); DVA: dynamic visual acuity (logMAR); DVA loss = DVA – static visual acuity (SVA); CI: 95% confidence interval

Table 4. Standard error of the measurement (SEM) and SEM% values for the GST and the DVA loss.

		Within-session			Between-session		
		SEM	SEM%	MDC	SEM	SEM%	MDC
GST	Left	35	26.9	97	42	32.3	
	Right	30	22.1	83	31	22.8	
	Up	39	29.8		37	28.2	
	Down	29	21.0		33	23.9	
DVA loss	Left	0.06	25.0	0.17	0.07	29.2	
	Right	0.08	32.0		0.08	32.0	0.22
	Up	0.10	62.5		0.11	68.8	
	Down	0.07	43.8	0.19	0.08	50.0	

GST = gaze stabilization test (deg/ sec); DVA loss = dynamic visual acuity – static visual acuity (logMAR); SEM = standard error of the measurement; MDC = minimal detectable change; SEM = SD $\sqrt{(1 – ICC)}$; SEM% = SEM/ mean * 100%; MDC = SEM * 1.96 * $\sqrt{2}$, MDC was calculated for measures with significant ICC values only.

Table 5. GST and DVA loss scores (means and standard deviations) in the horizontal plane for patients with peripheral lesion (n = 12) toward the lesion vs. non-lesion side.

| | Session 1 | | | | Session 2 | |
| | 1st repetition | | 2nd repetition | | 3rd repetition | |
	Non-lesion side	Lesion side	Non-lesion side	Lesion side	Non-lesion side	Lesion side
GST	136 (42)	129 (29)	124 (47)	116 (50)	152 (51)	151 (39)
DVA loss	0.25 (0.08)	0.25 (0.07)	0.22 (0.14)	0.18 (0.14)	0.18 (0.09)	0.13 (0.12)

GST = gaze stabilization test (deg/ sec); DVA loss = dynamic visual acuity – static visual acuity (logMAR).

Table 6. Pearson product moment correlations between subjects' SVA and their GST scores.

			SVA		
			Session 1		Session 2
			1st repetition	2nd repetition	3rd repetition
GST	Left	Correlation	0.17	0.400	-0.146
		p-value	0.387	0.039	0.496
		n	28	27	24
	Right	Correlation	-0.056	0.237	0.341
		p-value	0.777	0.225	0.102
		n	28	28	24
	Up	Correlation	-0.003	-0.072	-0.384
		p-value	0.989	0.722	0.078
		n	27	27	22
	Down	Correlation	-0.058	0.017	0.031
		p-value	0.769	0.932	0.889
		n	28	27	23

GST = gaze stabilization test (deg/ sec); SVA = static visual acuity (logMAR); $\alpha = 0.01$

Table 7. Pearson product moment correlations between each GST score and the DVA loss score in the same direction for the three repetitions of testing.

			Session 1		Session 2
			1st repetition	2nd repetition	3rd repetition
GST and DVA loss correlations	Left	Pearson Correlation	-.299	**-.517****	-.222
		p-value	.123	**.006**	.309
		n	28	**27**	23
	Right	Pearson Correlation	.104	**-.606****	**-.529****
		p-value	.600	**.001**	**.009**
		n	28	**28**	**23**
	Up	Pearson Correlation	-.382	**-.715****	.139
		p-value	.049	**.000**	.549
		n	27	**27**	21
	Down	Pearson Correlation	-.279	-.378	-.119
		p-value	.151	.052	.597
		n	28	27	22

GST = gaze stabilization test (deg/ sec); DVA = dynamic visual acuity (logMAR); $\alpha = 0.01$

5.0 THE EFFECT OF OPTOTYPE AND VELOCITY PARAMETERS ON THE PERFORMANCE OF HEALTHY YOUNG ADULT SUBJECTS ON THE GAZE STABILIZATION TEST

5.1 ABSTRACT

The gaze stabilization test (GST) is a functional measure of the vestibulo-ocular reflex. The purpose of the current study was to examine the influence of the optotype (the letter E) size, presentation time, and head velocity on GST performance. Twenty one healthy young subjects (mean age: 26 ± 4, range $21 - 34$, 10 male) performed the computerized GST. Testing was repeated several times using different combinations of the optotype size and presentation time over a wide range of head velocities (less than 60 to greater than 220 deg/ sec). The sizes examined were 0.20, 0.25, and 0.30 logMAR above the subject's static visual acuity (SVA). The presentation times examined were 20, 30, and 40 msec above subject's minimum perception time (mPT). Performance varied considerably based on the optotype parameters used in the GST. The optotype combination of SVA + 0.20 logMAR and mPT + 20 msec was the most difficult combination with the average of all subjects' performance less than 64% at all velocities. The optotype combination SVA + 0.30 logMAR and mPT + 40 msec was the easiest combination with subjects being able to correctly identify the optotype at any head velocity with greater than 70% average accuracy. Increasing the head velocity in any size/time combination caused

deterioration in subjects' performance. Our study findings show that optotype parameters have significant influence on subjects' performance on the GST.

5.2   INTRODUCTION

In recent years there has been growing interest in functional tests of the vestibulo-ocular reflex (VOR), namely the dynamic visual acuity (DVA) [40, 43, 44, 47, 60, 61, 88-91] test and the gaze stabilization test (GST) [6, 25, 77, 105, 106, 108]. The VOR helps to stabilize vision during head movements by producing eye movements that are equal in magnitude and opposite in direction to the movements of the head [31, 59, 90]. Maintaining clear vision during head movements requires stabilizing the images of objects on the fovea (the area of the retina with maximum visual acuity) [22]. Dysfunction of the VOR causes deterioration of vision during head movements, which can lead to postural instability and increased risk of falling [35, 108].

The DVA test estimates the size of the smallest optotype (e.g. the letter E) that a subject can clearly see during head movement [46]. Dynamic visual acuity is then compared to the visual acuity with the head stationary to produce a visual acuity loss score. The visual acuity loss equals the dynamic visual acuity minus the static visual acuity (SVA) (DVA loss= DVA – SVA). The GST estimates the maximum head velocities a subject can achieve while still being able to correctly identify the orientation of a fixed-size optotype [25, 106].

The performance of healthy subjects during the DVA and GST tests varies widely. Young healthy subjects' horizontal DVA loss scores have been reported as 0.043 (SD = 0.048) [46], 0.26 (SD = 0.13) [101, 102], 0.189 (SD = 0.072) [25], and 0.13 (SD = 0.07) [105] logMAR.

The use of different test parameters may help to explain the variability across the studies. For example, various testing distances have been used in both tests. Distances used for the DVA test include 1.5 m [6], 2 m [43-46, 84, 89, 90], 3 m [25], and 4 m [105]. Distances used for the GST include 1.5 m [6, 7, 77, 106, 108], 3 m [25], and 4 m [105]. In addition, the velocity of head movement during the DVA test has been variable. Some studies have used 120 – 180 degrees/ sec as the range of head velocity during DVA testing [6, 43, 44, 46, 89] while others have used 85 – 120 degrees/ sec [105]. Optotype size has also varied between studies. During the GST, optotype increments of 0.20 [77, 108], 0.25 [105, 106], and 0.30 [25] logMAR above subjects' SVA have been used.

In addition, the duration of the presentation of the optotype can be manipulated. An optimal optotype presentation time would be long enough to allow for identifying the orientation of the optotype using the VOR but not too long to allow for other eye movement control systems to be used to identify the target. While the VOR has latencies as short as 5 msec, the latency of saccades is around 100 msec [59]. If the presentation time is less than 100 msec, it is unlikely that the saccadic system can assist in identifying the target. Presentation times have varied in the literature between 40 – 75 msec [25, 77, 108]. A few studies have not reported the presentation time used for the DVA [43, 44, 46, 89] or the GST [27]. Other studies have used presentation times that were adjusted according to each subject's minimum perception time (mPT) [105, 106]. The mPT is the shortest presentation time required for an optotype to appear on the screen for the subject to correctly identify the orientation of the optotype. Adjusting the presentation time according to the subject's mPT assures that each subject is provided enough time to visualize the target. However, in the case of a patient with a very slow mPT (>70 msec), the optotype presentation time may be so long that saccades could compensate for a deficient VOR.

The purpose of the current study was to examine the influence of optotype size, presentation time, and velocity of head movement on subjects' performance on the GST in young healthy adult subjects. The results of the study should be helpful in selecting the optimal parameters for the GST.

5.3   METHODS

5.3.1   Subjects

Twenty-one young healthy subjects were recruited for this study (mean age = 26 years, SD = 4, range = 21 – 34, 10 male). Subjects were University students with no history of neurological disorders. Subjects were excluded from the study if their visual acuity (with corrective eye wear) was worse than 20/40. The study procedures were approved by the Institutional Review Board at the University of Pittsburgh. All participants signed the written consent before the start of research activities. Subjects were tested with best corrected vision.

5.3.2   Experimental procedure

The InVision™ device (NeuroCom International, Inc., Clackamas, OR, USA) was used for testing. The procedure used for testing was described previously [69]. In summary, testing started with measuring the subject's SVA and mPT. The SVA test measured the size of the smallest optotype that a subject could see and identify correctly without any time constraints.

The mPT test measured the shortest duration of the optotype presentation that a subject required while still being able to correctly identify the orientation of the optotype. The SVA and mPT were then used as baseline for further testing of the VOR. During all testing an optotype (the letter E) was presented on the computer screen. The open end of the E was pointing either up, down, right, or left and the subject was asked to determine the orientation of the E. Testing distance was 4 meters. The device was placed in a quiet room with room light measured at 70 lux. The operator viewed a separate computer screen to control testing.

The size of the E was reported in logMAR units. A logMAR is a logarithm of minimal angle of resolution [39] and is the standard unit for measuring visual acuity [40, 89]. The InVision system uses the best Parameter Estimate by Sequential Testing (the best PEST) adaptive algorithm to control the progress of testing and calculate the subject's SVA and mPT scores. The original PEST algorithm was developed by Taylor and Creelman as an adaptive procedure to measure psychometric properties [99]. A modification of the original method was proposed by Pentland; the best PEST adaptive algorithm [72]. The best PEST algorithm is an efficient procedure, requiring the fewest number of trials to reach scores with good precision [58].

The outcomes of the SVA and mPT tests were used as the baseline for testing with head movement. Three increments of the optotype size were examined; 0.20, 0.25, and 0.30 logMAR above the subject's SVA. As for the presentation time, three increments were examined; 20, 30, and 40 msec above the subject's mPT. These optotype size and presentation time increments were chosen because they match the increments that were already used in the available literature. A head mounted sensor (an InterSense Inertia Cube[2], 3-axis integrating gyro) was placed on each subject's head to provide feedback about head velocity and range of head motion.

5.3.2.1 Choice of optotype size and presentation time combination

At the beginning of this research study, the first 9 subjects were tested using 3 out of the 9 possible optotype combinations. The 3 combinations used for testing were randomly chosen for each subject. Later, guidelines were developed to select the combination of optotype size and presentation time (Figure 5). The 9 subjects who were tested on 3 random combinations returned to be tested using the guidelines. At the end of this research study, one optotype combination, i.e. an optotype size of SVA + 0.30 logMAR and a presentation time of mPT + 40 msec, was chosen as preferred combination for future testing. Subjects who were not tested using this combination (n = 9) were asked to come back to perform the test using this combination. Seven out of the nine subjects were able to come back for testing.

During the testing of any combination, optimal performance was defined as having correct responses on greater than 50% of the trials at the velocity range 140 – 179 deg/ sec. If subjects were able to achieve ≥ 50% correct responses at the velocity range 140 – 179 deg/ sec, this was considered a good performance at this combination.

- Testing started with the combination of the smallest optotype size (SVA + 0.20 logMAR) and shortest presentation time (mPT + 20 msec) (Combination A).
- The next trial utilized a larger optotype size (SVA + 0.25 logMAR) and a longer presentation time (mPT + 30 msec) (Combination B).
- If the subject performed well on combination B, 2 more trials were performed:
    - A trial with the same optotype size as combination B but shorter presentation time (mPT + 20 msec)

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- A trial with same presentation time as combination B but smaller optotype (SVA + 0.20 logMAR)

- If the subject did not perform well on combination B, the next trial utilized a larger optotype size (SVA + 0.30 logMAR) and a longer presentation time (mPT + 40 msec) (combination C).

- If the subject performed well on combination C, 2 more trials were performed:
    - A trial with same optotype size as combination C but shorter presentation time (mPT + 30 msec)
    - A trial with same presentation time as combination C but smaller optotype (SVA + 0.25 logMAR)

Figure 5. Flowchart of the guidelines used to determine optotype size and presentation time combination.

Combination A
(SVA + 0.20 / mPT + 20)

Combination B
(SVA + 0.25 / mPT + 30)

Perform well

Not perform well

Two combinations in random order:
1. Same optotype size (SVA + 0.25)
   Shorter presentation time (mPT + 20)
2. Smaller optotype size (SVA + 0.20)
   Same presentation time (mPT + 30)

Combination C
(SVA + 0.30 / mPT + 40)

Perform well

Not perform well

Two combinations in random order:
1. Same optotype size (SVA + 0.30)
   Shorter presentation time (mPT + 30)
2. Smaller optotype size (SVA + 0.25)
   Same presentation time (mPT + 40)

Stop testing

SVA = static visual acuity; mPT = minimum perception time.
Perform well: ≥50% correct responses at 140 – 179 deg/sec head velocity.
Not perform well: <50% correct responses at 140 – 179 deg/sec head velocity.

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5.3.2.2 The velocity of head movement

Once an optotype size and presentation time combination was chosen, testing commenced with head movement in the yaw plane. The optotype was presented on the computer screen only when the head velocity required in each trial was reached. Data obtained from the head mounted sensor was used to provide feedback to the patient and the technician regarding the velocity and range of head movement.

Subjects were first instructed to move their heads in the yaw plane at a slow speed (<60 deg/ sec). After 10 optotype presentations at this slow speed, subjects were asked to move at a speed between 60 and 99 deg/ sec. After another 10 presentations at the new speed range, head velocity was increased between 100 and 139 deg/ sec. The same pattern of velocity increase by increments of 40 deg/ sec was followed until the head velocity was greater than 220 deg/ sec. For any given combination, the test was stopped when the maximum head velocity (>220 deg/ sec) was achieved or when the percent of correct responses within any 2 consecutive velocity ranges was less than 50%. Subjects were asked to report any complaints of nausea, headache, dizziness, and visual blurring on a visual analog scale before and after each repetition of the test.

5.3.3   Data analysis

Box plots were made of the performance versus the velocity of head movement for each combination. The velocity bins corresponded to head velocities used in the test (<60, 60 – 99, 100 – 139, 140 – 179, 180 – 219, and > 220 deg/ sec). Performance was defined as the percentage of the number of trials in which subjects correctly identified the orientation of the

optotype divided by the total number of trials (correct response/ total number of trials).

Accordingly, 100% performance indicated correct identification of the optotype in all trials and

0% performance indicated inability to correctly identify the optotype orientation in any trial.

Means and standard deviations were also used to describe the performance.

In order to examine the influence of increasing the head velocity on performance at any

given optotype combination, a non-parametric repeated-measures analysis was performed across

the 6 velocity bins. A 2-way within-subjects analysis of variance was performed on a subsample

of 4 combinations to examine the effect of optotype size (SVA + 0.20 and SVA + 0.25 logMAR)

and presentation time (mPT + 20 msec and mPT + 30 msec) on performance. Analyses were

performed using PASW (version 18, SPSS Inc., Chicago, IL).

5.4   RESULTS

Figure 6 shows box plots of subjects' performance at the 9 different optotype size/ presentation

time combinations used in this study. For each combination, subjects' performance declined as

the velocity of head movement increased. The decline in performance as the head velocity

increased was significant ($p < 0.029$) in all combinations except one (SVA + 0.30 logMAR and

mPT + 20 msec, possibly due to the small number of subjects = 5). A 2-way analysis of variance

performed on the subsample of 4 combinations showed that increasing the optotype size and/ or

presentation time improved subjects' performance. With head velocity up to 179 deg/ sec,

increasing the optotype size or the presentation time significantly improved performance ($p <$

0.041). At 180 – 219 deg/ sec, increasing the presentation time, but not the size, improved

performance (p <0.01). The optotype combination A, (SVA + 0.20 logMAR and mPT + 20 msec), was the most difficult combination. In combination A, the average of subjects' performance at slow head velocities (<60 deg/ sec) was 63% (median = 50%, range 40 – 100 %), as the velocity of head movement increased, performance declined reaching an average performance of 36% at head velocities of >220 deg/ sec (median = 40%, performance range 0 – 75%).

Across all the different optotype combinations used in this study, at the slow head velocity range (<60 deg/ sec), the average performance ranged between 63 – 94% (median 56 – 100%). Combination C, optotype size (SVA + 0.30 logMAR) and presentation time (mPT + 40 msec) (Figure 6), was the only combination in which a majority of subjects (n = 12/17) scored 100% at the slow head velocity (median = 100%).

Subjects' symptoms of nausea, headache, dizziness, and visual blurring were monitored using a 10-cm visual analog scale. Only one subject had a minimal complaint of nausea after the repeated testing (mean = 0.4 cm, SD = 0.2), three subjects had headache following testing (mean = 0.5 cm, SD = 0.2). Dizziness symptoms were reported by 9 subjects (mean = 1.1 cm, SD = 0.7) and visual blurring by 8 subjects (mean = 0.9 cm, SD = 0.6). The other subjects did not report any symptoms following testing.
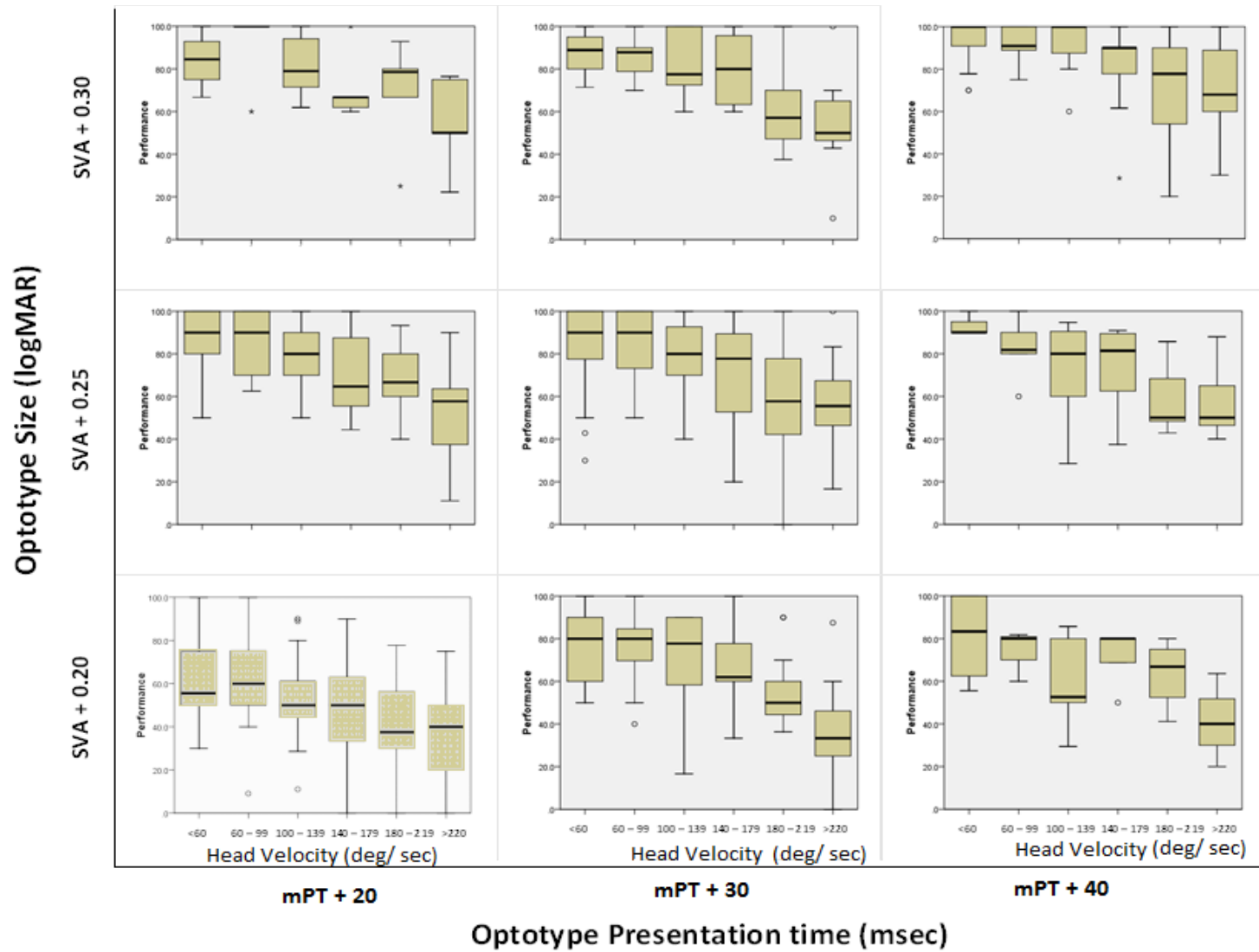
Figure 6. Boxplots of healthy subjects' performance on the nine combinations of optotype size and presentation time.

Performance is defined as the number of correct responses divided by the total number of trials at any given velocity range.

SVA = static visual acuity; mPT = minimum perception time

5.5   DISCUSSION

The gaze stabilization test scores in this study varied depending on the optotype parameters (size and presentation time) chosen for testing. Similarly, subjects' performance at a given optotype combination varied depending on the head velocity used for testing. Combination A, optotype size (SVA + 0.20 logMAR) and presentation time (mPT + 20 msec) was the most difficult combination for the GST. Previous studies have not reported the combination of SVA + 0.20 and mPT + 20, but have used a similar optotype size (SVA + 0.20 logMAR) with longer presentation times [77, 108].

Combination C, optotype size (SVA + 0.30 logMAR) and presentation time (mPT + 40 msec) (Figure 6), was the easiest combination. The average of subjects' ability to identify the orientation of the optotype correctly was between 70 – 94% across all head velocities. Goebel et al. used a combination similar to Combination C; the optotype size was 0.30 logMAR above the subject's SVA while the presentation time was always between 40 – 75 msec regardless of the subject's mPT [25]. While the testing distance in the current study was 4 m, Goebel et al used 3 m. Goebel et al results show good sensitivity, specificity, and reliability of the GST when using the large optotype size and presentation time [25].

The measurement of subjects' performance on the GST as a function of optotype size, presentation time, and head velocity has not been previously described in the literature. Previous studies have presented one GST score for each subject (a maximum head velocity score at a specific combination of optotype size and presentation time) [6, 25, 27, 77, 102, 105, 106, 108] whereas in this study nine combinations of various optotype sizes and presentation times were tested to determine which combination was the optimal combination for successful testing. It is

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clear from the data that some combinations would reveal little about the subjects' VOR abilities (SVA + 0.20 and mPT + 20; SVA + 0.20 and mPT + 30; SVA + 0.25 and mPT + 20), since so few people could successfully see the target even at slow head velocities when using these combinations.

It was interesting to note that healthy subjects' performance at very slow head velocities was not 100% accurate. Persons may have blinked or may have been not paying attention during the optotype presentation, making them unable to correctly identify the orientation of the optotype or even not see the optotype. Subjects also occasionally reported to the test administrator that the optotype was too small for them to see within the time frame.

The easiest size and presentation time combination was SVA + 0.30 logMAR and mPT + 40 msec. This combination resulted in the best performance across the widest range of head velocities. The authors recommend the use of this optotype combination for the GST in future studies with patients. Since the average performance of healthy subjects on this combination across all velocities was always >70% (median 68 – 100%), this could establish a criterion to be used when comparing the performance of patients and older subjects. Since healthy young subjects could not perform well at all velocities on all of the other 8 combinations, then patients and older subjects should not be expected to do so and these combinations will provide little information about the performance of these subjects. Older adults and persons with VOR dysfunction might need to start at this combination in order to determine if they have dysfunction.

The decline in subjects' performance as the head velocity increased while viewing optotypes of the same size and presentation time also has important implications when examining scores on a related test, the DVA test. As reported earlier, head velocities used for the

DVA test vary across studies. Dannenbaum et al [19] examined the influence of increasing the frequency of head movement while maintaining same range of the motion (i.e. equivalent to increasing the velocity of head movement) on performance on the clinical DVA test. Dannenbaum et al examined four frequencies of the head velocity in the yaw plane; 0.5, 1.0, 1.5, and 2.0 Hz. Their results indicate that the number of patients with abnormal scores increased as the frequency of the head movement increased. Essential differences exist in the methods used in the current study and that by Dannenbaum et al; the latter used the clinical DVA test in which there is continuous presentation of the optotype during the head movement, the head movements were performed passively, and the testing distance was 3.48 m. Results of both studies indicate that the head velocity chosen for the DVA test influenced the subject's score on the test.

Results of the current study demonstrate that the procedures used for the GST need standardization in order to enable comparison of results across laboratories. The use of different optotype parameters and testing protocols limits the generalizability of the results of different studies and makes the comparisons across different populations challenging. One of the limitations of the current study is that head movements were examined in the horizontal plane only. Vertical head movements should also be tested in future studies.

5.6   CONCLUSION

This study suggests that performance on the GST changes as the size and presentation time are manipulated. It is also clear that subjects' GST performance varies depending on the velocity of

head movement.   For future studies, the authors recommend the use of optotype size = SVA + 0.30 logMAR and presentation time = mPT + 40 msec for the GST since these criteria appeared to be associated with best performance by healthy young adult subjects.

6.0 PERFORMANCE OF YOUNG SUBJECTS FOLLOWING CONCUSSION ON A TEST OF GAZE STABILIZATION. A FEASIBILITY STUDY

6.1 ABSTRACT

Vestibular signs including dizziness and blurred vision are common following concussion. The computerized gaze stabilization test (GST) provides quantitative information about the dynamic capabilities of the vestibulo-ocular reflex (VOR). The purpose of the current study was to examine the performance of young subjects following concussion on the GST compared to healthy subjects. Twenty two subjects diagnosed with concussion (mean age: 19 ± 4, range 14 – 31, 9 females) and 19 control subjects (mean age: 25 ± 3, range 21 – 33, 10) were tested. The GST records the speed at which a subject could move their head while being able to correctly identify a target presented on a computer screen. Patients performed the dynamic visual acuity test and were also tested on a post-concussion neurocognitive test battery (immediate post-concussion assessment and cognitive testing, ImPACT) and completed the Dizziness Handicap Inventory (DHI) and the Activities-specific Balance Confidence (ABC) scale. Results show that there were no significant differences between the performance of patients and healthy subjects ($p > 0.25$). No differences were noticed between the performances of patients who were athletes versus the non-athletes ($p > 0.09$). there was a significant correlation between GST and DVA scores in the right direction (Spearman correlation = -0.54). There were no significant

correlations between patients' performance on the GST and their DHI, ABC, or ImPACT scores. The lack of significant differences may have been due to the chronicity of concussion in our sample (median duration since concussion = 14 weeks) and the inclusion of all patients post-concussion without objective vestibular abnormalities. Further study of patients following concussion with objective findings of VOR abnormalities may unravel more limitations in this patient group.

6.2   INTRODUCTION

Traumatic brain injury accounts for 1.2 million emergency department visits each year [83]. The majority of these visits are due to mild traumatic brain injury (concussion) (Centers for Disease Control Website). Concussion is defined as a pathophysiologic alteration in brain function following a direct or indirect blow to the head [63]. One of the most common injury mechanisms involves acceleration-deceleration of the head [63]. Neuroimaging studies, such as MRI or CT scan, usually reveal normal findings, however, advanced imaging techniques, such as diffusion tensor imaging, reveal damage to axons and axonal transport following a mild concussion [2, 16, 110].

Vestibular symptoms following a concussion are common; these include balance problems, headache, dizziness, blurred vision, and/ or difficulty concentrating [3, 26, 48, 68, 86]. Evidence suggests that vestibular involvement following a concussion can be due to problems in the vestibulo-spinal and the vestibulo-ocular reflexes (VOR) [48]. Hoffer et al [48] reported that

60% of retired and active duty military personnel post mild head injury who complained of dizziness had abnormalities of the VOR and the vestibulo-spinal reflex.

Objective outcome measures of the function of the VOR in patients following concussion have been recently reported in order to attempt to quantify vestibular function [3, 27, 48, 86]. The gaze stabilization test (GST) and the dynamic visual acuity (DVA) test provide quantitative information about the function of the VOR [25, 46, 89, 108].

The GST records the fastest speed at which subjects can move their heads while being able to correctly identify a visual target [25, 108]. The DVA records the smallest visual target that a subject can identify while moving the head at a fixed speed [43, 44, 46]. The GST and DVA have been used previously with patients with vestibular disorders to examine the function of the VOR [6, 25, 43, 44, 77, 89]. Patients with vestibular disorders generally perform worse than healthy control subjects on the DVA and GST demonstrating slower head velocities and greater visual acuity loss with head movement [6, 25, 43, 44, 77, 89]. Gaze stabilization performance in patients with vestibular disorders has been related to gait performance [108]. Dynamic visual acuity improvements have been noted in persons with unilateral and bilateral vestibular hypofunction after vestibular rehabilitation [43, 44].

The purpose of the current study was to compare the performance of young subjects with and without concussion on the gaze stabilization test. The relationship between the performance of subjects with concussion on the GST and the Dizziness Handicap Inventory (DHI) [53], Activities-specific Balance Confidence scale (ABC) [75], and the Immediate Post Concussion Assessment and Cognitive Testing (ImPACT test) [62] was also examined.

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6.3   METHODS

6.3.1   Subjects

Persons with concussion who presented to the University of Pittsburgh concussion clinic were eligible for the study. Twenty two young adults (mean age: 19 ± 4, range $14 - 31$, 9 females) who had experienced a concussion participated in this study. Patients were included in the study if the neuropsychologist believed that the patient could tolerate the head movement required by the GST. Of the 22 patients, 13 had acquired their concussion while engaged in athletic activities whereas the remaining 9 were involved in non-athletic incidents at the time of the concussion.

The performance of persons with concussion was compared to that of nineteen healthy young subjects without a history of concussion (mean age: 25 ± 3, range $21 - 33$, 10 females). The healthy subjects were tested on the GST as part of a previous research study [70]. Exclusion criteria for the healthy subjects included a diagnosis of a neurological disorder and visual acuity worse than 20/40. All of the healthy volunteers were University graduate students. The study was approved by the University of Pittsburgh Institutional Review Board and all subjects provided informed consent.

6.3.2   Experimental procedure

The experimental procedure for the GST and the DVA test has been described previously [69]. The InVision™ device (NeuroCom International, Inc., Clackamas, OR, USA) was used for

testing. Testing began with recording the size of the smallest optotype (the letter E) that a subject could correctly identify (static visual acuity, SVA, measured in logMAR) and the shortest presentation time (the time that the optotype was displayed on the screen) that a subject required to identify the orientation of the optotype correctly (minimum perception time, mPT, measured in msec).

Following the recording of the SVA and mPT, the GST was performed for head movements in the yaw plane. The optotype used during the GST was 0.30 logMAR above the subject's SVA and presented for 40 msec longer than the subject's mPT. This optotype combination was chosen because previous study has shown that healthy young subjects can perform well with this combination with greater than 70% accuracy in identifying the orientation of the optotype even at very fast head velocities [70].

During testing, a head mounted sensor (an InterSense Inertia Cube^2, 3-axis integrating gyro) was used to provide feedback about the velocity and the range of head movements. The GST started at a slow head velocity (<60 deg/ sec) and the velocity was increased in increments of 40 deg/ sec according to the subject's performance and tolerance until a maximum velocity at which the subjects could no longer identity the orientation of the optotype was reached.

At any velocity range, the optotype was presented for a total of 4 trials. If the subject was able to correctly identify the orientation of the optotype in all 4 trials (100% correct performance), the speed was increased to the next level. If the subject's performance was less than 100%, 4 more trials at the same speed were attempted. The test was stopped when 1) the maximum head velocity (>220 deg/ sec) was achieved, or 2) when the percent of correct responses within two consecutive velocity ranges was less than 50%, or 3) when the subjects could no longer tolerate the head movement.

The DVA test was performed after the GST. During the DVA test, subjects were asked to move their heads in the yaw plane at a constant head velocity (85 – 120 deg/ sec) while viewing the computer screen. The DVA test measured the size of the smallest optotype that a subject could correctly identify while moving the head. Scores (in logMAR units) were recorded for left and right-directed head movements and represent the loss in visual acuity between the dynamic and static head positions. Only patients performed the DVA testing. The GST and DVA testing were completed in 30 minutes.

Subjects' symptoms of nausea, headache, dizziness, and visual blurring were monitored throughout testing using a 10-cm vertical visual analog scale (VAS) [33]. Symptoms were monitored at the beginning of testing and after each head movement test (baseline, after GST left, after GST right, and after DVA). The change in VAS for each test was calculated by subtracting the score before each test from the score after the test.

Patients were asked to complete the ABC scale [75] and the DHI [53] at the time of gaze stability testing. Also, patients were timed while standing on an Airex foam pad with their eyes closed, for a maximum of 30 seconds. Patients were examined by neuropsychologists following the concussion and the ImPACT test [62] Version 3.0 was administered several times including the same day of the GST. The ImPACT battery takes approximately 20 – 25 minutes to administer and includes the following domains: attention, memory, processing speed, and reaction time. The ImPACT also includes a symptom checklist that each patient completed. The composite ImPACT scores consisted of a verbal memory, visual memory, visual memory speed, reaction time, impulse control score, and the symptom checklist scores.

6.3.3   Data analysis

Descriptive statistics were used to determine mean, median, and standard deviation (SD) for length of symptoms, DHI, ABC, ImPACT, and VAS scores. A non-parametric Mann- Whitney test was performed to determine if there were significant differences between the GST performance on the left and right directions between patients versus healthy subjects at each velocity , the GST performance of patients who complained of dizziness versus those who did not, the GST performance of patients who had physical therapy ordered versus those not referred for physical therapy, the GST performance of athletes versus non-athletes, and scores on the ImPACT symptom checklist between athletes versus non-athletes.

Spearman correlations were computed to determine if there was a relationship between GST and DVA scores, and between GST and ImPACT composite score. Spearman correlations were also utilized to compare the DHI total score to the ImPACT composite scores. The p value was set at $p < 0.05$ for significance. All analyses were performed using PASW (version 18, SPSS Inc., Chicago, IL).

6.4   RESULTS

The median time since concussion was 14 weeks (range 2 – 240 weeks). The median value since the time of concussion was reported because there were three patients who were 96, 209, and 240 weeks post-concussion. Of the 22 subjects, 15 patients had been referred for physical therapy intervention for subjective complaints of dizziness, headache, and/or imbalance. Of these 15

patients, 12 attended one or more physical therapy sessions. Three patients did not attend vestibular physical therapy although it was prescribed for them. Thirteen patients were athletes and 9 were non-athletes. All patients except one (20 year old, female; concussion duration 5 years) were able to successfully perform the 30-second standing on foam task.
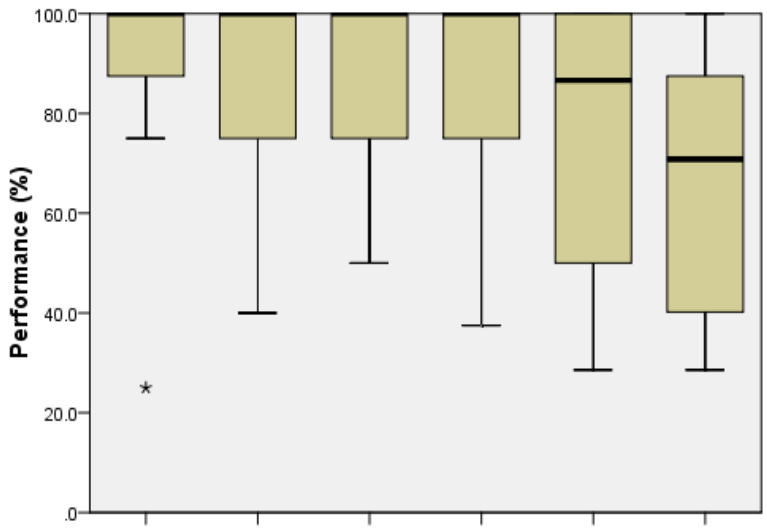
Boxplots of subjects' performance (percent of correct trials over total number of trials) versus the head velocity were created for patients with concussion and the healthy subjects (Figure 7). There was no significant difference between GST performance of young subjects with and without concussion at each velocity ($p > 0.252$). There were no significant differences between the performances of patients who complained of dizziness versus those who did not. All patients except one were able to complete the DVA and the GST, and all healthy subjects were able to complete the GST. Only one patient could not move their head to the right fast enough to get 50% or more correct responses at <60 deg/ sec. There was a significant relationship between the GST and DVA scores in the right direction in the patients with concussion (Spearman correlation = -0.54). No significant correlations were noticed between GST and ImPACT composite scores (all $r < 0.40$)

When examining the GST performance of patients who underwent physical therapy vs. those who were not referred to physical therapy, there were no significant differences between the two groups ($p > 0.058$). There were no significant differences between the performances of athletes versus non-athletes on the GST ($p > 0.09$). The ImPACT symptom checklist scores ranged from 0 – 43 with a mean of 12 (SD 13). There was a significant difference in the symptom checklist items in athletes versus non-athletes ($p < 0.04$). Athletes reported fewer symptoms than non-athletes (mean = 7 versus 21) (Table 8).

Composite DHI scores and the subscale scores (physical, functional, and emotional) and ABC scores are included in Table 8. Dizziness Handicap Inventory scores ranged from 0 – 42 and the ABC scores ranged from 59 – 100%. There were no statistically significant differences between athletes and non-athletes on the DHI and ABC. However, it was interesting to note that the non-athletes had overall less balance confidence than the athletes. There was a relationship between the total DHI score and the verbal memory composite score of the ImPACT ($p < 0.05$) were higher DHI scores (more handicap) correlated with higher verbal memory composite scores (slower responses, Spearman correlation = 0.44). No other relationships were noted between the DHI and the other ImPACT composite scores.

The VAS scores pre and post testing are included in Table 9. One outlier was removed from the analysis under the nausea category (7.7 out of 10) after completing the DVA testing. All others had a change in nausea scores that was either 0 or that had improved (less nausea) after completing the DVA. With the outlier removed the average nausea score was -0.04.

The symptoms most commonly experienced by patients with concussion as indicated on the ImPACT symptom checklist were headache (n=15), difficulty concentrating (n=12), fatigue (n=10), dizziness (n=10), sensitivity to light (n=9), and difficulty remembering (n=9). Other symptoms noted on the symptom checklist include feeling mentally foggy (n=8) and problems with balance (n=8). All other symptoms were experienced by less than 8 patients following concussion.

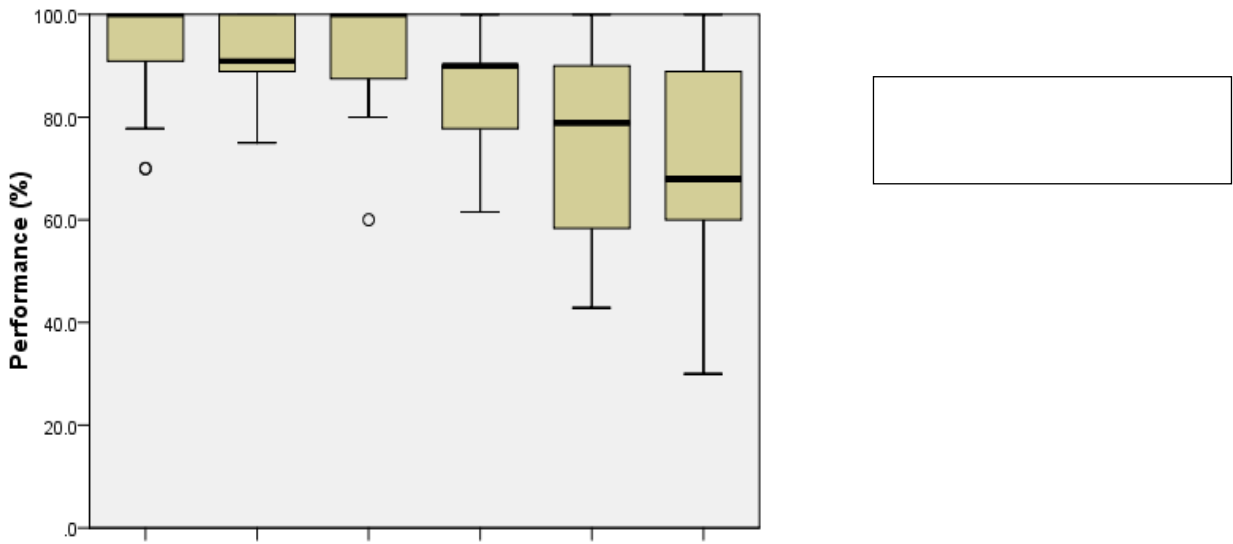A. Patients with concussion on head movement to the right
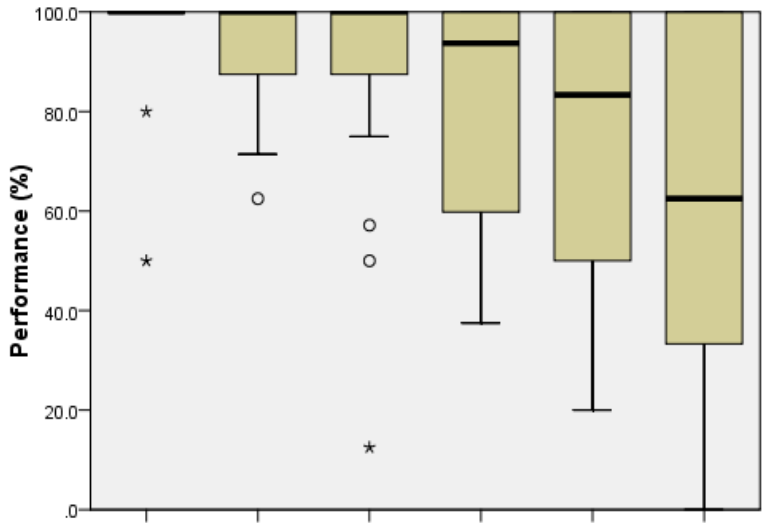
Figure 7. Box plots of subjects' performance on the gaze stabilization test (GST)

Y-axis: Performance indicates the percent of correct trials over the total number of trials.

X-axis: The velocity was divided according to the velocity ranges used during testing.

Table 8. Dizziness Handicap Inventory (DHI) total scores plus physical, functional, and emotional subscores; Activities-specific Balance Confidence (ABC) Scale; ImPACT composite scores (verbal memory, visual memory, visual motor speed, reaction time, and impulse control); and ImPACT symptom checklist scores for all patients, athletes, and non-athletes (mean, SD).

	Total Group (n=22)	Athletes (n=13)	Non-athletes (n=9)
DHI	16 (11)	16 (9)	16 (14)
DHI physical	7 (6)	6 (5)	8 (8)
DHI functional	5 (4)	6 (4)	4 (4)
DHI emotional	4 (4)	4 (3)	5 (5)
ABC	92 (11)	94 (7)	89 (14)
Verbal Memory	88 (12)	89 (12)	86 (11)
Visual Memory	73 (11)	73 (12)	73 (9)
Visual Motor Speed	41 (10)	39 (11)	43 (9)
Reaction Time	0.59 (0.15)	0.61 (0.17)	0.55 (0.11)
Impulse Control	8.3 (6)	10 (8)	6 (4)
Symptom Checklist score	12 (13)	7 (7)	21 (16)*

*p<0.05

Table 9. Visual analog scale (VAS) scores (mean, SD) on nausea, headache, dizziness, and visual blurring in patients following concussion and healthy subjects. Scores are reported at before testing and the change in VAS after gaze stabilization (GST) and dynamic visual acuity (DVA) tests.

		Nausea	Headache	Dizziness	Blurred Vision
Subjects with concussion	Baseline	0.1†	2.6 (2.1)	0.7 (.8)	2.1 (2.9)
	After GST Left	0	0.5 (1.1)	1.6 (1.9)	0.3 (0.9)
	After GST Right	0	0	-0.1 (1.1)	0
	After DVA	0	-0.2 (0.7)	-0.3 (1.3)	0.1 (0.6)
Healthy subjects	Baseline	0	0	0	0.3 (0.6)
	After GST Right	0	0	0	0

† No standard deviation because only one person experienced nausea.

6.5   DISCUSSION

There was no difference noted between GST performance in young persons with and without concussion. It was expected that a difference in GST scores would be seen between persons with concussion and healthy controls. None of the persons post-concussion had vestibular laboratory testing, which is a limitation of the current study. However, 46% of the persons post-concussion reported dizziness on the ImPACT symptom checklist suggesting that they may have either peripheral or central vestibular dysfunction. Since most persons post-concussion have resolution of symptoms within four weeks post-concussion [17, 104], patients with concussion in our study who complained of dizziness were not typical of young persons who have experienced a concussion.

The lack of differences on the GST between healthy controls and persons post-concussion might also be explained by the optotype parameters (size and presentation time) chosen in this study. The current optotype combination (SVA + 0.30 logMAR and mPT + 40 msec) may have been too easy for the subjects to view during active head movement, thus making the task simple and therefore, unable to discriminate between people with and without concussion. Another concern with the current optotype combination is that in subjects with poor visual acuity or perception time the optotype presented during the head movement testing may be too large or presented long enough to allow other eye movement systems to help in keeping the focused gaze.

Another possible explanation for the lack of significant differences is that the VOR may not be impaired in all persons post-concussion; Hoffer et al [48] reported that 60% of their mild head injury group had objective evidence of VOR abnormality. The wide range of duration since

concussion might have resulted in less people having vestibular symptoms, since vestibular symptoms may resolve over time post-concussion. Finally, the inclusion criteria for this study which required that the neuropsychologist examining the patients believed they could tolerate the head movement required for testing might have resulted in the inclusion of patients who have already recovered VOR function.

The lack of significant differences between the performance of patients who were referred to physical therapy and those not referred to therapy ($p \geq 0.058$) could have been due to the small number of subjects in the current study (type II error). A larger number of subjects is expected to increase the power of the sample and reflect significant differences. No power analyses were conducted for the purposes of this study because there are no baseline data about the test in this patient group in the literature.

A significant relationship was observed between GST and DVA scores in the right direction in patients following concussion (Spearman correlation = -0.54). As expected, the correlation between the two scores was negative indicating that higher scores on the GST test (i.e. faster head velocities) correlated with less visual acuity loss on the DVA test during head movement.

There was no relationship between GST scores and composite scores on the ImPACT. Finding no relationship between the GST and ImPACT scores was somewhat surprising since many of the symptoms that the persons with concussion experienced, which included to dizziness, headache, and difficulty concentrating are often symptoms that persons with vestibular disorders also experience [86]. Persons with vestibular dysfunction perform worse on the GST compared to control subjects [25]. The ImPACT symptom checklist identified common vestibular-like symptoms experienced by our subjects following concussion: headache, mentally

foggy, dizziness, balance difficulties, difficulty with memory/concentration, and sensitivity to light. The ImPACT test did not relate to GST scores, suggesting that they are measuring different concepts.

The overall mean of 16 on the DHI indicates that this study sample would be considered "mildly" handicapped as a result of dizziness [109]. There were no differences between athletes and non-athletes on the DHI, yet there were significant differences noted on the ImPACT symptom checklist between athletes and non-athletes with the non-athletes experiencing more symptoms after the concussion. The ImPACT symptom checklist may be more sensitive at identifying problems that young patients experience as a result of a concussion, it is also possible that athletes may not be willing to disclose their symptoms in order to return to play more quickly. The DHI was not designed to assess function post-concussion, although many of the symptoms reported by persons post-concussion are included in the DHI such as difficulty reading, difficulty with vigorous activities such as dancing, difficulty concentrating, interference with job responsibilities, and restriction of travel. Our patients' scores on the DHI and ABC show that our sample was less affected compared to Alsalaheen et al [3] who reported a mean DHI of 37 and a mean ABC of 78% in their sample of persons post-concussion. Alsalaheen et al's sample was a mix of older and younger persons post-concussion [3] while our sample included only young subjects following concussion.

It was surprising that all of the young people, excluding one person with longstanding concussion history, were able to stand on a piece of high density foam. Standing on foam with eyes closed was easily attainable. In older persons post stroke, falls from a foam pad relate to increased fall risk [21]. In young people, it appears that the foam pad with eyes closed test demonstrated a ceiling effect in our sample. Standing on foam with eyes closed is part of the

Balance Error Scoring System (BESS) [32] that is commonly performed on the sideline at sporting events to assess postural control after concussion. The average time since concussion was 36 weeks (SD 60 weeks) suggesting that our sample was more chronic. Most persons post-concussion have a resolution of their symptoms within 4 weeks [67]. It is possible that the persons post-concussion in our sample had already regained normal postural control, thus the standing on foam with eyes closed was accomplished successfully.

Visual analog scores for patients at baseline included symptoms of headache, blurred vision, and dizziness with only one person reporting nausea at the start of testing. Symptoms of headache, dizziness and blurred vision increased after testing GST left but stayed the same or got better with GST right testing and the DVA testing. The fact that the VAS scores of headache, dizziness, and blurred vision remained stable was of interest, as often movement induced symptoms increase with fast head movement [7]. The subjects were asked if they were comfortable continuing the testing and typically the rest period lasted 1-2 minutes. It is possible that patients were "learning" to tolerate the testing during the GST left. During subsequent GST right and DVA testing, the overall sample's symptoms stabilized or got better suggesting that there was not a cumulative increase in symptoms during testing. It is not clear if the stabilization of symptoms would be seen if we had tested GST right first. Others have reported visual blurring and oscillopsia during DVA and GST testing, suggesting that our patient's symptoms are typically experienced by persons with vestibular dysfunction [7, 43, 44, 89].

It may have been possible to differentiate if there were VOR abnormalities between control subjects and persons post-concussion if the persons post-concussion were tested sooner after onset of concussion. Additionally, a smaller optotype presentation might have better assisted in demonstrating if there were differences between the two groups. Due to the long

testing time in the current study (30 minutes) that was required to collect data across the range of head velocities in the right and left head movement directions, in addition to the DVA test, testing was performed in the horizontal direction only. Future studies should examine the performance of patients in the vertical direction.

6.6   CONCLUSION

There was no difference in young people with and without concussion on the GST. Also, no differences on the GST were noticed between athletes versus non-athletes following concussion or patients referred to physical therapy versus those not referred to therapy. There was no relationship between GST scores and ImPACT scores, DHI, or ABC scores in the patients tested.

7.0   DIRECTION OF FUTURE RESEARCH

The GST is a functional test of the VOR. Data obtained from patients' performance on the test will provide information about the limitations of patients' participation in different daily tasks and an objective method to track patients' recovery during vestibular rehabilitation. As we gain more information about the dynamic demands of different functional activities such as walking, running, and driving, the information provided by the GST becomes invaluable in determining the functional capabilities of patients with vestibular complaints and detecting their improvement over the course of therapy. This information might also guide future decisions such as when patients can drive or athletes return to play safely. In the first Aim, we provided evidence that the reliability of the InVision™ Tunnel system is less than desirable. We hypothesized that the choice of the best PEST adaptive algorithm to run the test may have been inappropriate to produce a reliable test. In addition, no clear justification for the choice of the optotype size and presentation time parameters was available in the literature.

In specific Aim 2, we examined the performance of young healthy adult subjects on the GST in the yaw plane using nine different optotype size and presentation time combinations. Our results show that the performance of healthy subjects on the GST varied considerably based on the optotype combination used for testing. Based on the results of this study, we decided to

choose an optotype size 0.30 logMAR above subjects' SVA and a presentation time 40 msec longer than subjects' mPT for further research.

In Aim 3, the performance of young subjects following concussion on the GST was compared to that of healthy young subjects. The performance of the patients following concussion was also correlated with their scores on different measures. No significant correlations were found between the performance of patients and healthy subjects or scores on ImPACT, DHI, or ABC scale.

The three stages of the current study raise more questions than answers. Future research should examine the reliability of the "new" InVision GST using the new optotype parameters. An algorithm to reach a single final score on the GST should be developed to replace the best PEST algorithm. Providing a single final head velocity score for each direction of head movement on the GST will be desirable to provide a quick summary for therapists to compare the performance across patients and track the recovery of patients over the course of therapy. At the same time, the authors believe that examining the performance of subjects over a wide range of head velocities by means of a performance curve would provide detailed information about the performance of the VOR across difference head velocities. The performance of subjects in the yaw plane was examined in Aim 2. Future studies should examine subjects' performance in the pitch plane. Differences between the horizontal and vertical VOR and the mechanics of the neck joints involved will certainly influence subjects' performance on the test.

Our sample size was 21 subjects in Aim 2 and 22 in Aim 3. Further research using a larger number of subjects should be conducted. In addition, we examined the performance of young subjects following head concussion in Aim 3. The choice of this population was mainly due to the ease to access a large number of this population at our facility. Future studies should

include patients following concussion with evidence of vestibular involvement. Also, patients should be recruited sooner after the concussion. Vestibular complaints following a concussion resolve over time in most patients [17, 104]. In addition, the performance of other patient populations, mainly patients with vestibular disorders, should be examined and cut-off values for clinically significant change should be established.

APPENDIX A

VISUAL ANALOUG SCALE FORM

The visual analog scale form used to obtain information about subject's nausea, headache, dizziness, and visual blurring before and after the performance of the head movement tests (the dynamic visual acuity and the gaze stabilization tests).

Date ___/___/____   Subject ID_____

VAS ____

_____

Please place a mark on the line below corresponding to how you **feel right now** when you are sitting regarding the following symptoms:

Nausea	**Headache**	**Dizziness**	**Visual Blurring**
As bad as it can be	As bad as it can be	As bad as it can be	As bad as it can be

| No nausea at all | No Headache at all | No Dizziness at all | None at all |

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