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A Normative Study of Rotational Vestibular Testing among U.S. Military Rotary-Wing Aviators

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14. ABSTRACT

The peripheral vestibular system contributes to spatial orientation by providing perception of body movement. Evidence suggests the vestibular function of pilots differs from that of non-pilots. Deficits to the vestibular system can lead to spatial disorientation, which is associated with aviation-related mishaps. However, aviator-specific normative data or criteria for return-to-duty or fitness-for-duty currently does not exist. The current medical recommendation is that pilots who experience vestibular deficits receive a comprehensive evaluation prior to returning to full flight duties. One such test that evaluates the perception of motion and gravity of both the peripheral and central vestibular systems is rotational chair (RC) testing. RC testing measures vestibular sensitivity to motion, vestibulo-ocular reflex (VOR) function, and the visual-vestibular interaction using multiple frequencies and test paradigms. The purpose of this study was to create a normative database of vestibular function in U.S. military trained aviators utilizing an RC. Fifty participants completed RC tests that utilized rotation in this study.

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14. Abstract (continued)

The RC subtests reported here include the: sinusoidal harmonic acceleration test, vestibular step test, subjective visual vertical (SVV), subjective visual horizontal, visual enhancement, visual suppression, unilateral centrifugation with SVV, and computerized rotational Head impulse test. Tests of oculomotor function were also completed, however these results are reported elsewhere. The established database can serve as a comparative cohort in test interpretation for military aviators.

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Introduction

Due to the inherent danger of the military pilots' occupational environment (e.g., an aircraft filled with combustible fuel in varied flight conditions), safety is of utmost importance (Shupak et al., 2003). The pilot's ability to maintain awareness of the attitude and position of the aircraft to an external point of reference (i.e., terrain), linear and angular velocity, linear acceleration, and gravity is key and known as spatial orientation (Bos, Bles, & De Graaf, 2002; Stott, 2013). Spatial disorientation, or the inability to perceive accurate direction of one's self and aircraft in relation to Earth, often results in fatal aircraft mishaps.

Spatial orientation is maintained by the integration of cues from the visual, vestibular, and proprioceptive sensory systems. The vestibular system cues provide the body's perception of movement. When the head moves, an automatic and compensatory movement of the eyes result. This fast-acting eye movement is the vestibulo-ocular reflex, or VOR (Parmet & Ercoline, 2008; Zalewski, 2017). The VOR permits a stable image to remain on the fovea of the retina during head or body movements, preventing or reducing retinal slip. Without the VOR, images of interest would appear blurry, indistinguishable, or unstable (Lee, Kim, & Park, 2004; Matta & Enticott, 2004; Stott, 2013). While flying an aircraft, the VOR of a pilot contributes to maintaining image stability (i.e., acuity) on the target of interest. Examples of the VOR in action while in-flight include use of a telescopic sight Zuma E Maia, Mangabeira Albernaz, Cal, Brusco, & Da Costa, 2015), or a helmet-mounted display (HMD) (Patterson, Winterbottom, & Pierce, 2007; Tung, Miller, Colombi, & Smith, 2014).

The vestibular system continues to provide information regarding spatial orientation for a pilot while in-flight. This is particularly true as visual and proprioceptive cues are often absent or misleading, like in that of a degraded visual environment (Shupak, Gordon, & Nachum, 2001; Parmet & Ercoline, 2008). However, the "vestibular system cannot adequately identify the movements of an airplane" (Tribukait & Eiken, 2012, p. 496), and therefore pilots are often instructed to disregard their perception of movement and rely upon their instrument readings.

The relationship between vestibular function, VOR, and the ability to maintain ocular control in the face of involuntary head movement, is one-reason pilots who have a vestibular deficit (i.e., vertigo, disequilibrium) should receive a comprehensive evaluation before returning to Active Duty or starting initial training (Clark & Rupert, 1992). Shupak et al., (2001) report that in young, fit, and healthy patient cohorts, central vestibular compensation results in the resolution of symptoms like that of vertigo, dizziness, imbalance (due to vestibular insult or injury) within days. This compensation is not proof of "vestibular repair or guarantee [of] proper vestibular function under non-terrestrial conditions" (Shupak et al., 2001, p. 109). Residual vestibular deficits and/or an insufficient VOR have been reported to be contributing factors for spatial disorientation (Klokker et al., 2004; Shupak et al., 2003). Vestibular deficits in military-trained pilots often present as "difficulty maintaining controlled flight in actual or simulated instrument meteorologic conditions" (Lee, Durnford, Crowley, & Rupert, 1996, p. 3).

Since the advent of flight, the aeromedical community has displayed interested in investigating the differences of the vestibular system in pilots compared to that of non-pilots. Multiple studies suggest that the vestibular function of aviators (i.e., pilots and flight students) differs from that of non-aviators Ahn, 2003; Aschan, 1954; Bos, Bles, & de Graff, 2002; Brandt Fluur, & Zylberstein, 1974; Fisher, & Babcock 1919; Lee, Kim, & Park, 2004; Pialoux et al., 1976; Schwarz & Henn, 1989). Repeated in-flight conditions alter vestibular perception and response (i.e., the VOR); this includes gravitational force changes, high-speed accelerations, and visual-vestibular mismatches (Ahn, 2003; Ashan, 1954; Lee, Kim & Park, 2004; Schwarz & Henn, 1989). Motion and acceleration in-flight occur in multiple planes of motion not typical with on-ground bipedal movement. While not directly tied to the flight experience, Todd, Rosengren, and Colebatch (2009) reported that the vestibular end organs are sensitive to low frequency vibrations. Rotary-wing aircrafts produce consistent vibration due to its dual rotors, gearbox, engine, and the aerodynamic flow while in flight (Tung, Miller, Colombi, & Smith, 2014). However, the amount of vibration exposure an occupant experiences within a rotary-wing aircraft differs from what is created by the aircraft; as the energy is often mitigated with use of additional equipment (e.g., seat cushions or energy attenuation seats) (Madison, personnel communication, 2017).

Rotational chair (RC) testing evaluates vestibular sensitivity to motion, VOR function, and the visual-vestibular interaction with passive whole body rotation at multiple frequencies and test paradigms. Modern day RC testing utilizes a high torque chair to provide repeatable and controlled whole-body rotations (i.e., side-to-side oscillations or impulses) stimulating the horizontal semicircular canal over a broad frequency range in the assessment of both peripheral and central vestibular function of the individual sitting within it (Zalewski, 2017). Rotational tests that assess the vestibular system include the sinusoidal harmonic acceleration (SHA) test, the velocity step test (VST), visual suppression, visual enhancement, subjective visual vertical (SVV), subjective visual horizontal (SVH), and unilateral centrifugation with SVV. The SHA and VST are two commonly used rotational tests in the evaluation of the vestibular system (Maes et al., 2008).

Though limited, the vestibular function of pilots and flight students has been investigated utilizing both experimental rotational tests (Ahn, 2003; Aschan, 1954; Bos, Bles, & de Graff, 2002; Brandt et al., 1974; Schwarz & Henn, 1989) and clinically available RC subtests (Ahn, 2003; Lee, Kim, & Park, 2004). Ahn (2003) evaluated pilots and non-pilots by measuring VOR gain and phase during a sinusoidal rotational test pre- and post-VST. Ahn (2003) suggests that VOR gain (i.e., the ratio between eye and head velocity) is the most important variable to use in differentiating pilots from non-pilots. Further, the VOR gain in the pilot cohort was suppressed compared to that of non-pilots after the VST. Ahn concluded that VOR suppression may be a skill that "plays a certain role in a real flight, in which pilots are often exposed to severe vestibular stimuli" (2003, p. 287).

Fisher and Babcock (1919) published one of the first known studies regarding in-flight effects on the vestibular system. The researchers investigated the effect of repeated rotation and acceleration due to flying and the sensitivity of the vestibular system and as measured by the presence (and duration) of nystagmus after the forceful stop of a manual turning chair among Army aviators. This results from this study found that under the study test conditions, "aviators do not lose their nystagmus as a result of the rotation and whirling to which they are subjected" (p. 781). The manual rotational chair test utilized by Fisher and Babcock (1919) utilizes a similar test paradigm as the VST. Schwarz and Henn (1989) used the VST found shorter time constants

(TC) (i.e., the time it takes for the VOR to reduce to 37% of its peak) among a cohort of flight students than that of non-pilots. This suggests that in fact, flight experience does influence how the vestibular system and VOR respond. Lee, Kim, & Park (2004) investigated the effect of flight experience on the VOR by using the SHA subtest. Results from this study found that VOR gain increased with flight experience, with no noted difference in VOR phase (i.e., the timing difference between eye and head reported in the total number of degrees the eyes lag behind the head). A significant difference in vestibular function between military aviators (i.e., pilots and flight students) with as few as 20 hours of flight training, and non-aviators (i.e., soldiers with no flight experience) was also reported (Lee, Kim, & Park, 2004).

Although the difference in vestibular function (i.e., perception) between pilots and non-pilots is well-supported (Ahn, 2003; Aschan, 1954; Bos, Bles, & de Graff, 2002; Brandt et al., 1974; Lee, Kim, & Park, 2004; Schwarz & Henn, 1989), the reason why is not well understood. Previous studies have suggested that the difference in vestibular function among pilots and flight students may be due to either vestibular adaptation (Bos, Bles, & de Graaf, 2002; Lee, Kim & Park, 2004; Zuma E Maia et al., 2015) or habituation to the flight environment (Aschan, 1954; Bos, Bles, & de Graaf, 2002; Pialoux, et al., 1976; Schwarz & Henn, 1989). Vestibular adaptation is a reduced response due to prolonged stimulation (Collins, 1974). As where vestibular habituation is a long-lasting change of the central vestibular system due to neural plasticity after repeated stimulation typically evidenced as a response reduction (Collins, 1974; Clément, Tilikete, & Courjon, 2008; Gordon, Spitzer, Doweck, Shupak, & Gadoth, 1996).

As observed in the SHA subtest, vestibular habituation is evidenced as a decrease in VOR gain and increase in phase lead, particularly in low frequency (< 0.01 Hz) rotations (Jager & Henn, 1981 as cited in Lee, Kim, & Park, 2004). Interestingly enough, Lee, Kim, and Park (2004) report a cohort of pilots whose SHA VOR gain was greater than the anticipated non-pilot normative value range, and attribute these changes to vestibular adaptation. This finding suggests that pilots may not have a heterogeneous response in vestibular perception, and there may be a range of function both above and below the non-pilot normative values. As observed with the VST, vestibular habituation is expressed as reduced VOR gain, and shortened TC (Blair & Gavin, 1979; Bos, Bles, & de Graff, 2002). These studies however, have focused mainly on high-performance pilots, presumptively fixed-wing aircrafts or fighter pilots, and not that of rotary-wing aircrafts. Finally, in humans, the exact (or an anticipated range) duration that habituation is retented is unknown. Previous research suggests that vestibular habituation in pilots can last months (Aschan, 1954) or that it is perhaps a permanent change (Piraloux, 1976).

As pilots and flight-students have been shown to process vestibular stimulation differently than that of non-pilots, the use of normative values, developed from the general population (i.e., non-pilots) to interpret vestibular function, could result in an inaccurate interpretation of a pilot's or flight-student's test responses. The number of studies with published RC normative values using military aviators for any contemporary clinical RC assessment however, is limited. Further, RC testing lacks a standard approach for test parameters. This makes the comparison of RC test results to those obtained from outside vestibular clinics or labs difficult. These three reasons may fuel the recommendation to develop and use local site-specific normative data with the same equipment and test paradigm that will be used in a treatment facility (Fife et al., 2000; Goulson, McPherson, & Shepard, 2014; Maes et al., 2008; Zalewski, 2017). Therefore, prior to any study on a subclinical population of military aviators (e.g., flight students and pilots prone to motion sickness), local normative values must be established. The purpose of this study was to define the normal range of function among a clinically normal cohort of healthy military aviators utilizing tests of oculomotor function and rotational movement using a commercially available RC.

Methods and Materials

The goal of the current study was to create a normative database for multiple tests of oculomotor (e.g., smooth pursuit, saccades) and vestibular function (e.g., SHA, crHIT) utilizing the results of at least 40 U.S. military-trained aviators (Active Duty, Reserve, and National Guard). The U.S. Army Medical Research and Materiel Command Institutional Review Board approved this study. All participants signed an informed consent and received monetary compensation for their time.

Participants

Fifty-three participants were consented and screened for inclusion in the current study. All participants were U.S. military trained aviators (rated rotary-wing pilots or flight students) who held medical clearance for flight operations and had no reported history of vestibular, balance, or oculomotor difficulties. Data was not collected if a participant did not meet inclusion criteria (*n* = 1) or analyzed if a participant was withdrawn from the study (*n* = 3). Participants who reported accrued flight hours less than 20 hours (*n* = 1) were also excluded from analysis. Thus, the remaining data from 48 (47 male; 1 female) military-trained aviators (Active Duty, Reserve, and National Guard), aged 23 to 40 (32.3 ± 4.0) years were included for initial analysis. Data were further excluded if the recorded responses were questionable (e.g., anticipatory reactions or guessing was suggested). As seen in Table 1, the sample size used in the development of the database varied by RC subtest.

Table 1. Number of Participants Included for Analysis by Subtest.

SHA	VST	VE	VS	SVV	SVH	UC-SVV	crHIT
47	46	47	44	43	43	43	47

All prospective participants were told of exclusion/inclusion criteria prior to enrollment, allowing for self-exclusion without collecting any data. To ensure participants met inclusion criteria (Figure 1), participants were screened with two questionnaires that were not specific to the exclusion criteria. The first was a protocol-specific demographic questionnaire, which asked questions such as, but not limited to: birth year, total flight-hours, aircraft rated to fly, and medication (prescription and over-the-counter) use. The second questionnaire participants completed was the Dizziness Handicap Inventory (DHI) (Jacobson & Newman, 1990). The DHI mean (SD) score was zero (0).

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- History of traumatic brain injury (TBI) with symptoms in the past 6 months
- History of participation in organized sports/recreational activities that would result in physical contact and injury to the head with symptomology of TBI in the past 6 months
- History of exposure to high-level blast
- Known history of oculomotor disorders
- Diabetes
- Self-reported confirmed or possible pregnancy
- Consumption of:
    - alcohol for 24 hours prior to participation
    - nicotine for 2 hours prior to participation
    - food/drink for 2 hours prior to participation
- Prior disorders of hearing and balance including:
    - Ménière's disease
    - Chronic Migraine headaches
    - Multiple Sclerosis
    - Vestibular neuritis
    - Vestibular schwannoma
    - Sudden sensorineural hearing loss
    - Whiplash injury within the past 5 years
    - Cerebrovascular disorders
    - Systemic disorders (e.g., chronic renal failure, cirrhosis of the liver)
    - Iatrogenic injury to the head, ear, neck, and/or back

Figure 1. Study exclusion criteria.

Equipment

The I-Portal® Neuro-Otologic Test Center (NOTC) with VEST™ software (version 7.5.2) (Neuro Kinetics, Inc., Pittsburgh, PA)* was used. The NOTC system includes an off-set RC assembly, laser target generator, full-field OKN stimulus, isolation enclosure, with patient audio (through two-way headset with microphone) and video monitoring (through infrared cameras), and I-Portal® Visual Occlusion Goggles (VOG) digital eye tracking system. The participant monitoring system includes infrared video cameras focused on the enclosure, the RC, and the participant's face/upper torso. The VEST™ software controls all aspects of the system (e.g., VOG goggles, RC movement), and a full-feature analysis platform from which the relevant dependent variables can be derived (e.g., gain, symmetry, and phase).

Procedure

Test Conditions and Test Battery

All participants were familiarized to the RC, enclosure, and test conditions during the informed consent process. This included review of the equipment, restraints, enclosure, and test

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* See manufacturer's list.

conditions. During the review, each participant was told that all tests were completed in the dark, often without any visual stimulus at which to look. After informed consent and questionnaires were completed, the study personnel assisted the participant into the RC, secured him/her with the proper restraints, and fit the participant with the audio headset and VOG goggles. As seen in Figure 2, restraints used were used at both sides of the head, both feet, knees (above and below), shoulder, lap, and the upper chest. The communication headset and goggles were donned prior to head restraint application. The goggles were firmly affixed to prevent any slippage or accidental movement during testing. The communication system was then tested to ensure appropriate volume levels before closing the NOTC door. During testing, the participant was in constant audio communication with study personnel and monitored via infrared video images.

Figure 2. RC with VOG goggles and restraints.

All subtests were conducted with the lighting inside the enclosure turned off. A ventilation fan was used unless otherwise requested by the participant to be turned off due to comfort. All participants were encouraged to report any feeling of discomfort. Participants could take a break or withdraw from the study at any time. A brief description of the subtests, along with chair movement and visual stimulus details used, are described in Table 3. Participants were given the option to take breaks or rest periods between tests; breaks were not required. Participation in all subtests of the study protocol was estimated not to exceed two hours.

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Table 2. Vestibular Test Battery

Test	**Description**	**Chair Movement**	**Visual Stimulus**
Oculomotor Test Battery*	Spontaneous Nystagmus; Smooth Pursuit (horizontal/vertical); Saccades (horizontal/vertical); Gaze (horizontal/vertical); Optokinetic Nystagmus	None	Multiple
Smooth Harmonic Acceleration (SHA)	Chair oscillates clockwise (CW) to counter clockwise (CCW) with the vertical axis of rotation at center of the participant's head; measures the steady-state response of the VOR. Requires mental tasking.	0.01, 0.02, 0.04, 0.08, 0.16, 0.32, 0.64, 1.28, 1.75 Hz; peak velocity = 60°/ sec	None
Velocity Step Test (VST)	Chair moves CW, stops, then CCW, and stops; process is then mirrored (CCW-stop-CW-stop); measures transient response of the VOR and velocity storage. Requires mental tasking.	Peak velocity = 60, 240°/sec	None
Visual Enhancement (VE)	RC completes SHA movements while diffuse lights are projected on the enclosure wall. The participant is directed to look at but not to fixate on the lights as they pass.	0.04, 0.08, 0.32, 0.64, 1.28 Hz	Static full field optokinetic stimulus
Visual Suppression (VS)	RC completes SHA movements while a laser dot is projected onto the enclosure wall. The participant is directed to fixate on the dot while the chair is rotating.	0.04, 0.08, 0.32, 0.64, 1.28 Hz	Laser dot that moves with the chair
Subjective Visual Vertical (SVV)	Adjust a non-vertical line projected onto enclosure wall to (perceived) vertical via control buttons 6 times; measures oculogravic perception of vertical	None	Vertical laser line preset between 15 to 20°
Subjective Visual Horizontal (SVH)	Adjust a non-vertical line projected onto enclosure wall to (perceived) vertical via control buttons 6 times; measures oculogravic perception of horizontal	None	Horizontal laser line preset between 15 to 20°
Unilateral Centrifugation with SVV (UC-SVV)	The participant completes SVV task as many times as possible while at max velocity (300°/sec). Testing occurs while the RC is on- and off-center.	Peak velocity = 300°/sec; translation = 3.85 cm; 60 sec in each position	Vertical laser line
Computerized Rotational Head Impulse Test (crHIT)	Ten (5 CW, 5 CCW) whole-body short earth-vertical axis high impulse rotations.	Peak velocity = 150°/sec; Acceleration = 1004°/sec^2	Laser dot

* Tests of oculomotor function are not included in this report.

Data Collection

All participants completed a demographic questionnaire and the Dizziness Handicap Inventory (Jacobson & Newman, 1990) following the consent process to rule out any exclusion criteria that would prevent participation in the study. If any answer provided indicated that a participant met an exclusionary criterion (figure 1), the participant was then withdrawn from the study.

Prior to data collection using the RC, each participant completed a calibration test using the eye tracking goggles. The purpose of this "pre-test" was to determine the participant's eye amplitude in relation to the known displacement of the visual stimulus. The information provided from this test, allows for all future testing (within the same test session) to be scaled appropriately. This was repeated any time the VOG goggles were removed or changed position on the head. Since calibration testing does not result in any appreciable data for analysis, it is not discussed further in this report. Tests that evaluated oculomotor function (i.e., smooth pursuit, spontaneous nystagmus, optokinetic, horizontal gaze, vertical gaze, horizontal saccades, and vertical saccades) were also completed. As the purpose of this report is to discuss measurement of the vestibular system utilizing a RC, the procedure, methods and results from the oculomotor function tests are not reported here.

With the dynamic movement of the RC, the sensitivity and function of the vestibular system can be evaluated via recording and measuring the VOR. Movement of the whole body stimulates the peripheral vestibular systems in both the right and left ears, eliciting the VOR (i.e., nystagmus). Nystagmus is only indicative of a pathology when present in the absence of vestibular stimulation (Zalewski, 2017). When a visual stimulus (e.g., laser dot or line) was not provided during a subtest, the participant was tasked with alertness exercises to minimize any suppression of nystagmus. Some examples of "mental tasking" exercises used were to list items alphabetically or to complete simple mathematical equations.

The variables analyzed for each subtest, along with brief descriptions, are found in Table 3. For more information regarding RC test parameters and outcome variables, the interested reader is encouraged to refer to Brey, McPherson, and Lynch (2008a); Stockwell and Borjab (1997); or Zalewski (2017).

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Table 3. Selected Rotary Chair Response Parameters.

Subtest	Variable	Description
SHA	Gain	Ratio between the eyes' peak slow phase velocity and the chair (i.e., head) peak velocity
	Phase	Time between the measured eye and chair movement, reported in the number of degrees (°) the eye lags behind chair movement; inversely related to the VST time constant (TC)
	Asymmetry	Percent difference between gain measured during rightward and leftward rotations
VST	Gain	Ratio between the peak slow phase component eye velocity and chair velocity
	Asymmetry	Percent difference (of gain) elicited from rightward and leftward rotations at both per- and post-rotation
	TC	Amount of time (sec) it takes for 37% VOR gain decay
VE	Gain average	Ratio between eye slow phase component to chair velocity
	Phase	Difference in time between eye and chair movement
	Symmetry	Difference between gain right and left gain, reported as a percent
VS	Gain average	Ratio between eye slow phase component to chair velocity
	Phase	Difference in time between eye and chair movement
	Asymmetry	Percent difference between gain measured during rightward and leftward rotations
	Gain reduction	Percent difference between SHA and VS at the same chair frequency
SVV	Mean Error	Average ° deviation of line from 0° vertical
SVH	Mean Error	Average ° deviation of line from 0° horizontal
UC-SVV	Mean Error	Average ° deviation of line from 0° vertical, reported for right, center and left axis of rotation
crHIT	Gain	Reported for right and left impulses
	VOR weakness	Difference between gain right and gain left, reported as a percent

Statistical Analysis

The mean (M) and standard deviation (SD) for the selected response parameters (i.e., outcome variables, table 4) was calculated using IBM® SPSS® Statistics version 23.0 (Armonk, NY). Eye movement (i.e., nystagmus) analysis was automatically performed using the Neuro-Kinetic, Inc® VEST™ (v7.5.2) computer program software. Nystagmus recordings were reviewed for accuracy, with spurious responses removed prior to final VEST™ and SPSS analysis. Normative values were calculated using two standard deviations from the mean.

Results

SHA

The SHA subtest results obtained from 47 participants was included for analysis. Mean and SD for the parameters of gain, phase and symmetry are reported in Table 4. The mean VOR gain increased as the chair frequency increased. Typically, for RC frequencies below 1 Hz, the gain is anticipated to measure less than 0.5 or 50% (Brey et al., 2008a; Zalewski, 2017). This was also shown to be the case with the current study. The overall measured phase decreased as frequency increased from 0.01 to 0.32 Hz. Symmetry ranged from 4° to 15°, with only the highest frequencies achieving near 0°. The normative range found in Table 5 and are shown in figures 3, 4, and 5.

Table 4. Sinusoidal Harmonic Acceleration Mean and Standard Deviation.

	0.01	**0.02**	**0.04**	**0.08**	**0.16**	**0.32**	**0.64**	**1.28**	**1.75**
Gain	0.31 (0.16)	0.34 (0.19)	0.36 (0.20)	0.36 (0.18)	0.34 (0.20)	0.36 (0.20)	0.43 (0.22)	0.77 (0.21)	0.90 (0.24)
Phase	44.40 (9.82)	84.96 (8.17)	11.94 (7.88)	3.60 (7.89)	-1.96 (25.06)	-0.50 (15.94)	12.22 (9.09)	8.79 (4.88)	4.07 (7.08)
Asymmetry	8.06 (11.73)	15.18 (11.18)	12.32 (11.60)	13.47 (11.21)	11.74 (10.68)	11.23 (16.31)	4.10 (12.25)	0.67 (2.66)	-0.08 (3.25)

Note. Responses are M (SD).

Table 5. Sinusoidal Harmonic Acceleration Test Normative Ranges.

	0.01	**0.02**	**0.04**	**0.08**	**0.16**	**0.32**	**0.64**	**1.28**	**1.75**
Gain	-0.03 to 0.63	-0.04 to 0.7	-0.04 to 0.76	-0.01 to 0.73	-0.08 to 0.74	-0.04 to 0.75	-0.02 to 0.88	0.35 to 1.19	0.43 to 1.37
Phase	24.75 to 64.3	8.46 to 41.51	-3.98 to 27.89	-12.4 to 19.48	-52.69 to 48.63	-32.79 to 31.58	-6.15 to 30.60	-1.10 to 18.57	-10.26 to 18.37
Asymmetry	-15.7 to 31.67	-7.45 to 37.75	-11.17 to 35.73	-9.24 to 35.81	-9.75 to 33.38	-21.82 to 44.01	-20.72 to 28.81	-4.68 to 6.06	-6.50 to 6.48

Note. Normative ranged developed using M ± 2SD.

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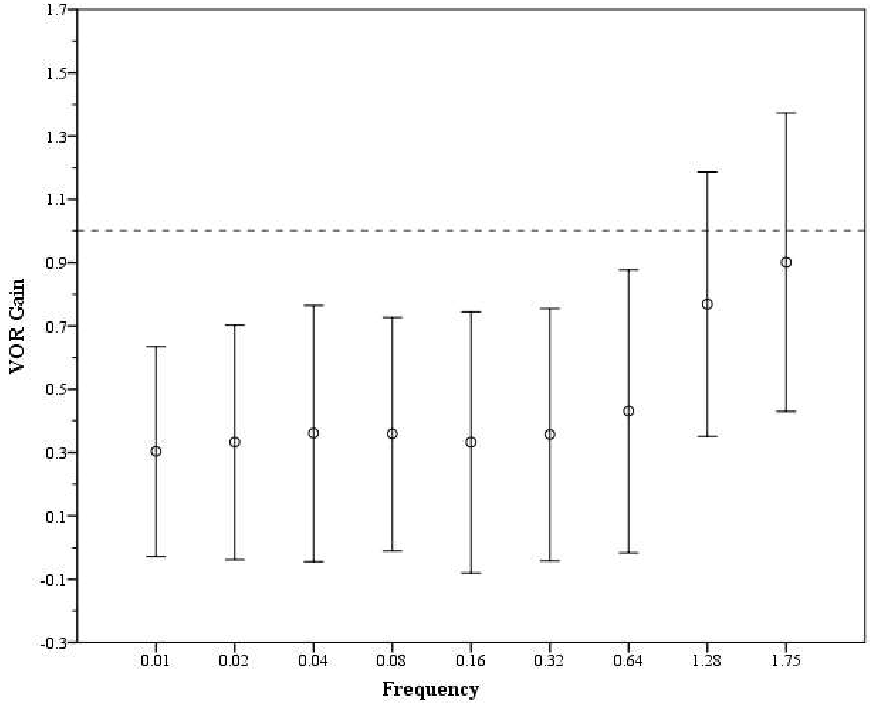

Figure 3. Developed Normative Range for SHA VOR Gain. Note. Normative ranges were developed using ± 2SD from the mean. Reference line indicates a gain of 1.0, or response unity.

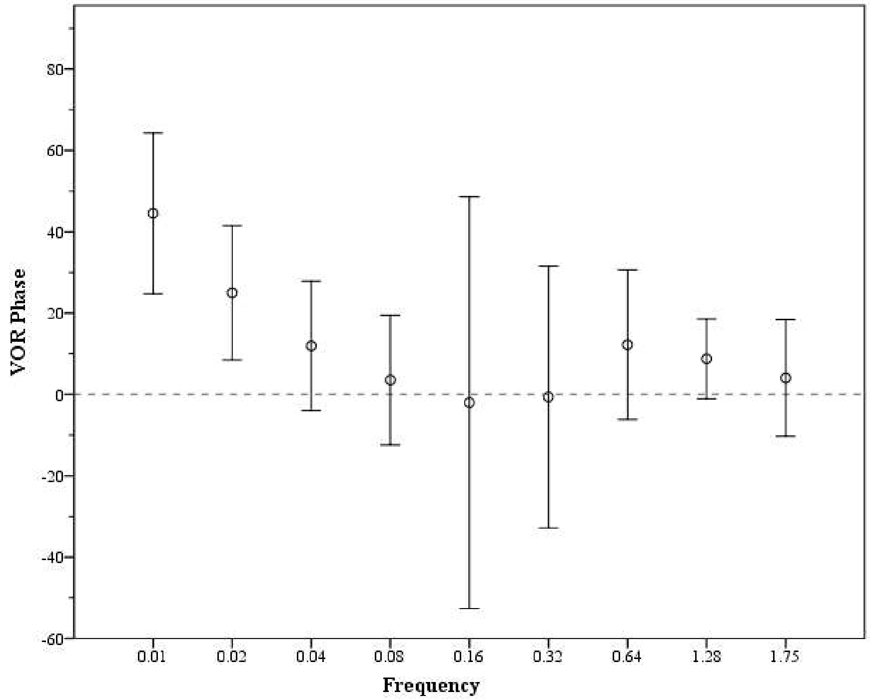

Figure 4. Developed Normative Range for SHA VOR Phase. Note. Normative ranges for test frequencies were developed using ± 2SD from the mean.

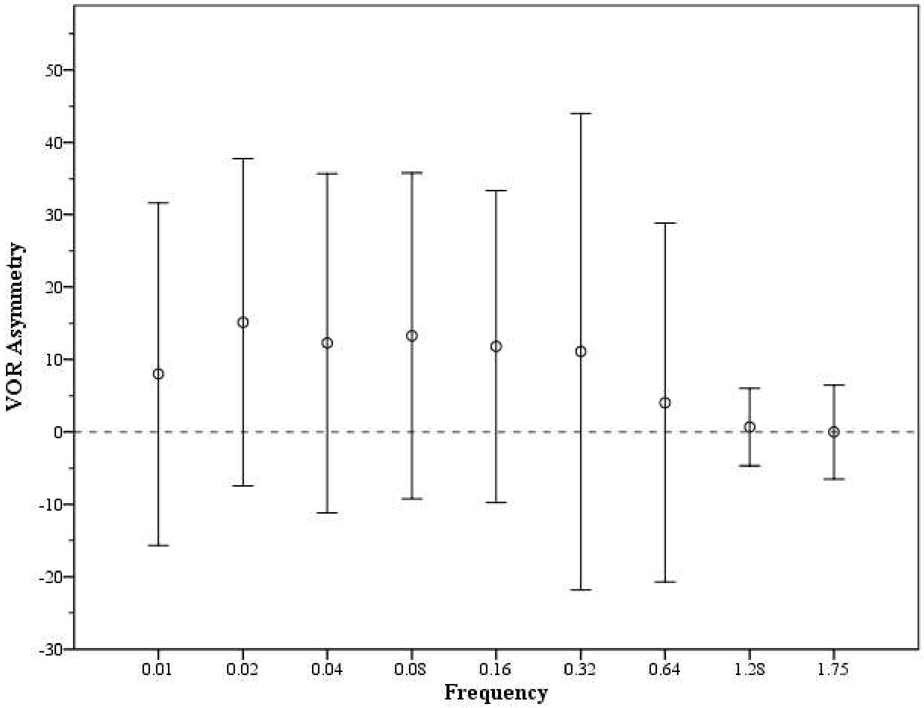

Figure 5. Developed Normative Range for SHA VOR Asymmetry. Note. Normative ranges for test frequencies were developed using ± 2SD from the mean.

VST

The data of 47 participants was included for analysis. Mean and SD for gain, TC, and symmetry for peak velocities of 60 and 240 °/sec is reported in Table 6. The developed normative range for TC is reported in Table 7.

Table 6. Velocity Step Test Results.

60 °/sec				
	Per-Rotary	**Post-Rotary**	**Per-Rotary**	**Post-Rotary**
Gain	0.58 (0.27)	0.58 (0.28)	0.57 (0.26)	0.62 (0.21)
TC	9.76 (5.71)	12.47 (6.82)	9.35 (5.72)	9.87 (7.47)

240 °/sec				
	Per-Rotary	**Post-Rotary**	**Per-Rotary**	**Post-Rotary**
Gain	0.59 (0.18)	0.67 (0.18)	0.58 (0.18)	0.69 (0.15)
TC	6.72 (2.53)	7.29 (2.62)	6.34 (2.73)	6.59 (2.57)

	60 °/sec	**240 °/sec**
Asymmetry	4.35 (18.23)	1.57 (8.60)

Note. Responses are M (SD).

Table 7. Velocity Step Test Normative Data.

60°/sec				
	Per-Rotary	**Post-Rotary**	**Per-Rotary**	**Post-Rotary**
Gain	0.04 to 1.13	0.03 to 13.92	0.05 to 1.08	0.19 to 1.04
TC	-1.66 to 21.18	-1.17 to 6.82	-2.09 to 20.8	-5.07 to 24.82

240°/sec				
	Per-Rotary	**Post-Rotary**	**Per-Rotary**	**Post-Rotary**
Gain	0.24 to 0.94	0.31 to 1.03	0.22 to 0.93	0.38 to 0.99
TC	1.66 to 11.78	2.05 to 12.54	0.89 to 11.79	1.46 to 11.72

	60°/sec	**240°/sec**
Asymmetry	-32.12 to 40.81	-15.64 to 18.78

Note. Normative Values were developed using M ± 2SD.

Visual-Vestibular Interaction Tests: Enhancement and Suppression

For the visual enhancement (VE) subtest, data from 47 participants were included in analysis. Mean and SD for gain average, phase and symmetry measured for the VE subtest was calculated (Table 8). The developed normative range for VE performance is reported in Table 9.

Table 8. Visual Enhancement Results.

	0.04	**0.08**	**0.32**	**0.64**	**1.28**
Gain Average	0.850 (0.207)	0.871 (0.228)	0.915 (0.227)	0.983 (0.142)	1.094 (0.142)
Phase	3.664 (3.661)	1.263 (5.976)	1.290 (3.517)	2.765 (2.751)	3.598 (3.647)
Asymmetry	3.383 (5.411)	1.189 (5.809)	0.396 (3.232)	0.730 (1.705)	0.264 (1.546)

Note. Responses are M (SD).

Table 9. Visual Enhancement Normative Data.

	0.04	**0.08**	**0.32**	**0.64**	**1.28**
Gain Average	0.44 to 1.26	0.42 to 1.33	0.46 to 1.37	0.70 to 1.27	0.81 to 1.38
Phase	-3.66 to 10.99	-10.69 to 13.22	-5.74 to 8.32	-2.74 to 8.27	-3.70 to 10.89
Asymmetry	-7.44 to 14.20	-10.43 to 12.81	-6.07 to 6.86	-2.68 to 4.14	-2.83 to 3.36

Note. Normative data was developed using M ± 2SD.

For the VS subtest, data from 44 participants were included in analysis. Mean and SD for gain average, phase and symmetry measured was calculated (Table 10). The total percent in VOR gain reduction was calculated for each participant at each test frequency. The overall mean percent gain reduction was calculated for the cohort and reported in Table 10 and Figure 6. The calculation used to determine the gain reduction percent was [1-(VS VOR gain/SHA VOR Gain)*100].

Table 10. Visual Suppression Results.

	0.04	**0.08**	**0.32**	**0.64**	**1.28**
Gain Average	0.057 (0.030)	0.058 (0.033)	0.071 (0.033)	0.120 (0.056)	0.428 (0.148)
Phase	11.01 (28.96)	6.45 (25.58)	8.81 (24.16)	14.83 (28.31)	12.45 (11.74)
Asymmetry	12.64 (16.86)	7.82 (23.92)	2.08 (21.45)	-2.93 (20.72)	-0.90 (5.68)
Gain Reduction	80.2 (14.7)	82.5 (8.4)	76.5 (11.8)	72.4 (11.0)	49.2 (16.7)

Note. Results are M (SD). Unit of measure: Gain Average (°), Phase (sec), Symmetry (%), Gain Reduction (%).

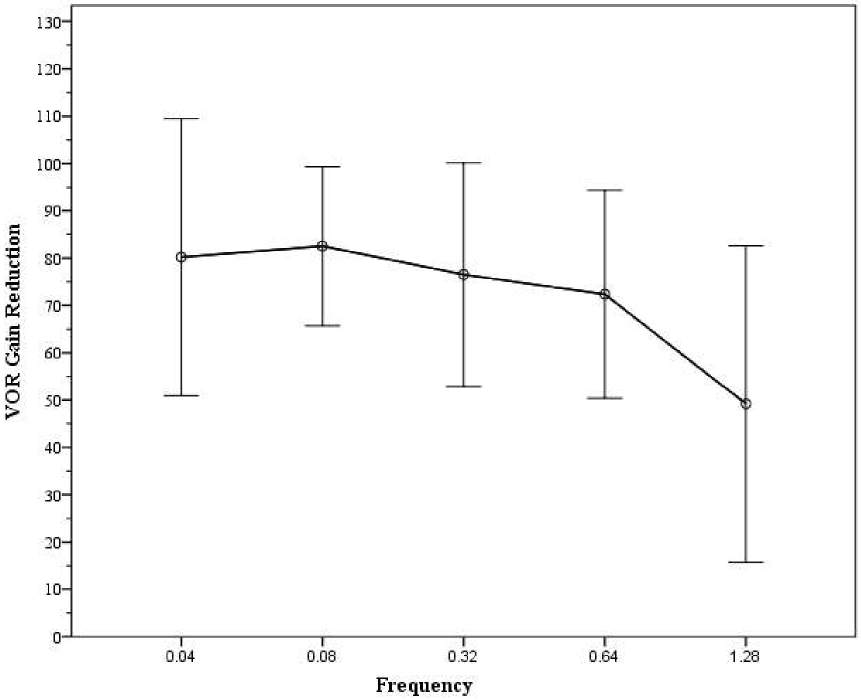

Figure 6. Calculated Percent of VOR Gain Reduction. Error bars indicate ± 2 SD from the mean.

The assumption was made that an abnormal response would present itself only as an inability to suppress the nystagmus generated, and therefore would result in a larger recorded gain value. The developed normative range for the VOR gain is reported in Table 11.

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Table 11. Visual Suppression Normative Data.

	0.04	**0.08**	**0.32**	**0.64**	**1.28**
Gain Average	0.63	0.71	0.74	1.23	0.72
Phase	49.9 to 68.93	-44.71 to 57.61	-39.51 to 57.12	-47.79 to 71.45	-11.04 to 35.93
Asymmetry	-21.07 to 46.35	-40.02 to 55.65	-40.83 to 44.98	-44.37 to 38.51	-12.27 to 10.47
Gain Reduction	51 to 110%	66 to 99%	53 to 100%	50 to 94%	16 to 83%

Note. Normative values were developed using M + 2SD. The assumption that abnormal function for gain average is >2SD (i.e., a lack in suppression), so M + 2 SD was used instead.

Static SVV, Static SVH, and Dynamic SVV

The data from 43 participants were used to calculate the overall degree error for M, SD, and normative data. Normative values were developed using both ± 1 SD and ± 2 SD from the mean. All results are reported in Table 12.

Table 12. Static Subjective Visual Vertical and Horizontal Overall Error with Normative Range.

	sSVV	**sSVH**
M (SD)	-0.9 (1.7)	-1.0 (1.6)
± 1 SD	-2.6 to 0.8	-2.6 to 0.6
± 2 SD	-4.3 to 2.5	-4.3 to 2.3

To account for the participant's baseline perception of earth vertical (i.e., static SVV or sSVV) in the interpretation of the dynamic or UC-SVV, a correction factor (CF) must be applied (Mango, Makuta, & Kiderman, 2011). Therefore, the applied CF is UC-SVV – sSVV (González, King, & Kiderman, 2014). The CF was completed for UC-SVV right (UC-R), center (UC-C), and left (UC-L) for each participant. The CF (i.e., UC-SVV – sSVV) was applied to all mean UC-SVV participant averages. Both the overall uncorrected mean score and the corrected mean score values are provided in Table 13, and can be seen in Figure 7.

Table 13. Unilateral Centrifugation with Subjective Visual Vertical Overall Error with Normative Range.

	UC-SVV			**Corrected UC-SVV**		
	Right	**Center**	**Left**	**Right**	**Center**	**Left**
M (SD)	-3.8 (3.31)	-1.2 (2.9)	2.0 (2.9)	-2.8 (2.6)	-0.3 (2.3)	2.9 (2.6)
± 1 SD	-7.1 to -0.5	-4.1 to -1.7	-0.8 to 4.9	-5.4 to -0.3	-2.6 to 2.1	0.3 to 5.6
± 2 SD	-10.4 to 2.9	-6.9 to 4.52	-3.7 to 7.7	-8.0 to 2.3	-5.0 to 4.4	-2.3 to 8.2

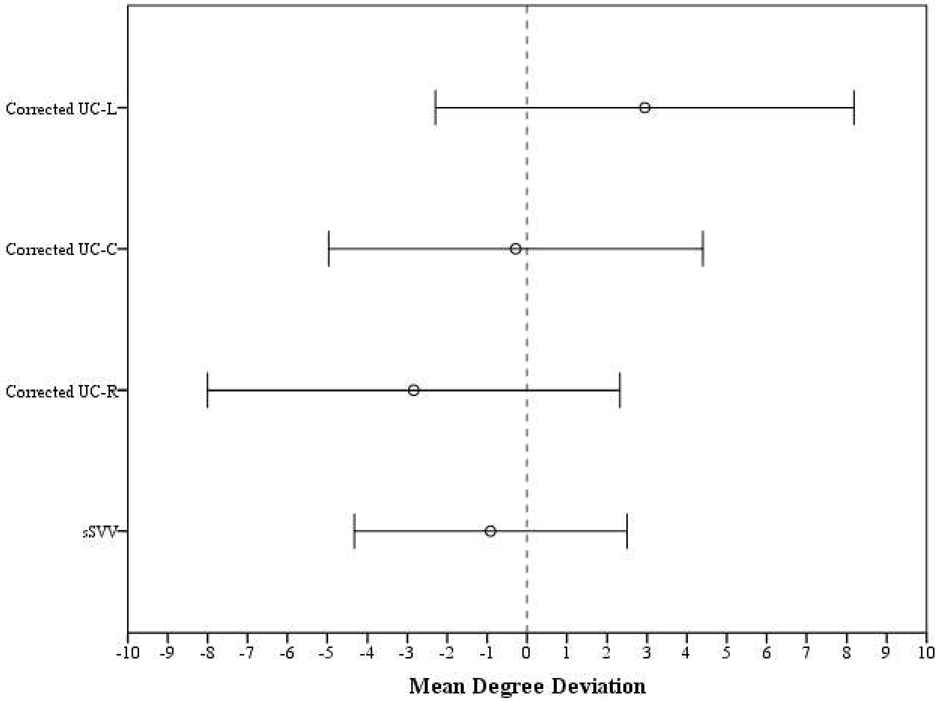

Figure 7. Normative Ranges for Static and Dynamic SVV. Confidence intervals (CI) are ± 2 SD from the mean. The dashed line indicates earth-gravity's of 0° vertical.

crHIT

The crHIT data from 47 participants was analyzed. The M, SD, and the lower limit of normal was calculated (i.e., M – 2 SD) for the gain – left, gain – right, and symmetry (table 14). The average gain was calculated using the gain left and gain right variables, and is also provided in Table 14.

Table 14. crHIT Response and Normative Cutoff.

	Gain – Left	Gain – Right	Gain – Average	Symmetry
M (SD)	0.92 (0.14)	0.94 (0.14)	0.93 (0.13)	1.09 (7.11)
-2SD	0.63	0.67	0.68	-13.13

Discussion

Repeated, routine exposure to changes in acceleration and gravitational force alters the way the vestibular system functions in pilots and flight students (Aschan, 1954; Lee, Kim, & Park, 2004; Pialoux et al., 1976; Schwarz & Henn, 1989). To our knowledge, these previous studies focused on fixed-wing pilots (e.g., fighter and/or transport) and did not include rotary-wing aviators. The goal of the current technical report is twofold. The first goal was to describe the vestibular function of clinically normal military rotary-wing pilots and flight students (with a self-reported minimum of 20 flight hours) who have medical clearance for flight operations using an RC test battery. The second goal was to derive normative values from the cohort. The RC test battery in this study incorporated clinically available tests of vestibular function that could be replicated using any commercially available RC.

SHA

The SHA subtest provides a measure of vestibular sensitivity to horizontal acceleration across a wide range of frequencies (0.01 to 1.28, and 1.75 Hz) via measurement of the VOR. The general trend for VOR gain is to increase as the rotational stimuli increase. In that regard, the findings in this study are in agreement with previous SHA normative studies (Li, Hooper, & Cousins, 1991; Maes et al., 2008; Durney, 2016; Zalewski, 2017). However, as seen in figure 8, the values of the current study's mean VOR gain is lower than other publically available normative datasets (Durney, 2016; Zalewski, 2017) using a comparable test paradigm (i.e., peak chair velocity of 60°/sec) at low rotational frequencies (less than 0.01 to 0.32 Hz). Individual variance (i.e., cohort SD) does not explain the difference between the current study pilot cohort and the normative study cohorts (Durney, 2016; Zawleski, 2017), as it is relatively similar (0.1 to 0.2) across all RC rotational frequencies.

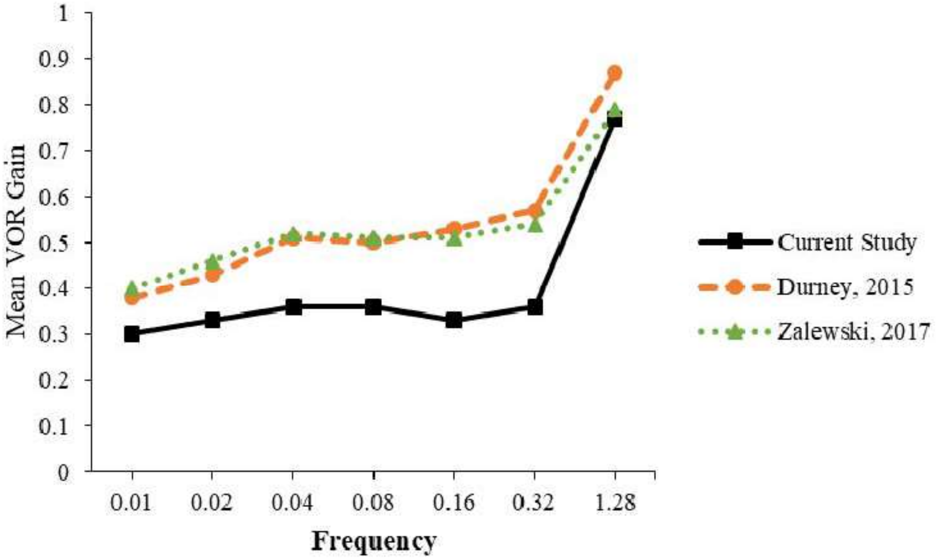

Figure 8. Comparing Normative Mean VOR Gain at Select Frequencies. Note. Comparative cohorts are publically available adult normative values, presumably non-military and non-pilot.

The reduced or suppressed VOR gain at low rotational frequencies (0.01 to 0.32 Hz) expressed in the current study's pilot and flight-student cohort would suggest an ability of gaze stabilization while moving side to side, in darkness. Participants were required to keep their eyes open during the entirety of the SHA subtests (could close eyes in between frequency trials), while the RC was moving, and they were not provided a visual target to aid in visual fixation. Similarly, Ahn (2003) found reduced SHA VOR gain after repeated rotations. At that time, Ahn (2003) concluded that pilots were able to suppress VOR gain after repeated rotations, and suggested that VOR suppression may be an important ability for pilots while in-flight. The findings from this study are in agreement.

Another study, that used a comparable 60 °/sec maximum velocity SHA test paradigm (recorded via electrooculography, or EOG, and not VOG), evaluated Air Force pilots (presumably fixed wing) to determine the effect of flight time on VOR gain (Lee, Kim, & Park, 2004). As seen in Figure 9, VOR gain increased as test frequency increased in both the current study cohort and the Lee, Kim, and Park (2004) pilot cohorts. However, Lee, Kim, and Park (2004) reported significant VOR gain increases among their pilot cohorts comparative to a non-pilot military control group. The study's findings indicate that there is not a statistically significant difference between VOR function of active pilots indiscriminate of the total number of accrued flight hours. Further, the authors conclude that the measured significant increase in VOR gain "observed in the pilot groups might be caused by adaptation by way of VOR plasticity rather than habituation" (p. 900). This is in direct opposition to our findings, as we found an overall reduction, or suppression, of VOR gain among rotary-wing military pilots when compared to publically available (non-pilot) normative values (Durney, 2016; Zalewski, 2017).

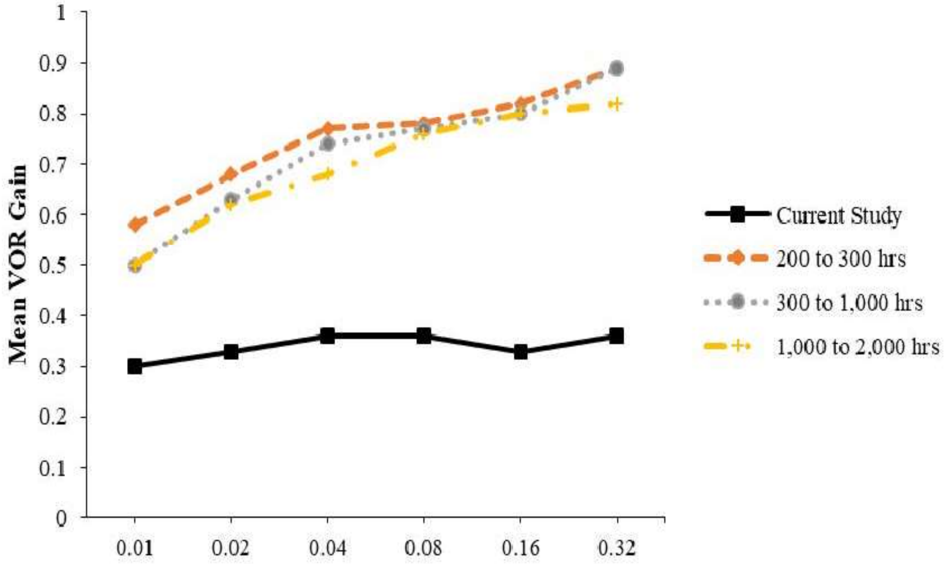

Figure 9. Comparison of Mean VOR Gain for Military Pilots at Select Rotational Frequencies. Note. The comparative pilot cohort data is from Lee, Kim, & Park, 2004. Mean VOR gain for the student pilot cohort either pre- or post- training was not available for comparison.

The discrepancy between these two military pilot studies (current study and Kim, Lee, & Park, 2004) may be due to participant characteristics (e.g., time-lapse since last flight, aircraft trained and rated to fly). Kim, Lee, and Park (2004) did not define the time since last flight for their active pilot population; however, this population was reported to have flown at least five times per week. We did not control for time since last flight, nor did we control for a minimum number of flight times per week. Vestibular adaptation is the observed change in vestibular perception during prolonged stimulation (Collins, 1974). Additionally, the type of aircraft (fixed- versus rotary-wing) and operational environment exposures (e.g., gravitational pull, acceleration, and vibration) may also be a contributing factor to pilot adaptation or habituation. That is, the vibration, in-flight movement, acceleration and gravitational pulls are fundamentally different between fixed- and rotary-wing aircrafts. This theory seems to be supported by the differences seen in high performance athletes such as ice skaters. Figure skaters are known to acquire vestibular adaptations due to repeat rotations and accelerations. However, Alpini, Botta, Mattei, and Tornese (2009) found that among ice skating specialties (i.e., pairs, singles, and dance), VOR gain differed depending on athletic maneuvers specific to the ice skating specialty. To conclude that the same would be true for the different specialties of pilots is likely a reasonable hypothesis given the differences found in studies with rotary wing versus fixed wing pilots. However, at this time, the literature searches for the comparison of vestibular function using any RC subtest between these two aviator cohorts have come up empty.

Reduced VOR gain is one sign of vestibular habituation (Jager & Henn, 1981 as cited in Lee, Kim, & Park, 2004). Therefore, it is possible that the current study's result of reduced VOR gain at rotational frequencies less than or equal to 0.32 Hz, comparative to non-military, non-pilots (Durney, 2016; Zalewski, 2017) indicates vestibular habituation in this study population of military rotary-wing pilots and flight-students. Reduced VOR gain can also be attributed to participant or patient inattentiveness, reduced mental alertness, fatigue, sleep deprivation, and stress (Matta & Enticott, 2004; Quarck, Ventre, Etard, & Denise, 2006; Zalewski, 2017). Participants were informed of the importance in maintaining mental alertness prior to the start of the RC test battery, and were tasked with mathematical calculations and/or questions to aid in maintaining their alertness. Although reduced mental alertness and fatigue are known to result in reduced VOR gain, the SHA test was one of the first subtests completed in the current study's test battery. Therefore, effects from both alertness and fatigue should have been mitigated. Other possible causes for the measured low VOR gain are either: insufficient vestibular stimulation and/or habituation of the pilots and flight students to the rotational stimuli used.

Phase, or the temporal difference between eye and chair (i.e., head) movement designated in degrees, is the most reliable test parameter of the SHA subtest (Li, Hooper, & Cousins, 1991). Mean VOR phase lead in a normal, healthy vestibular system, decreases as the RC frequency increases. According to Zalewski (2017), measured phase lead is greatest at 0.01 Hz. Phase lead (i.e., values greater than than 0°) indicates that the participant's recorded eye move in advance of (i.e., lead) the chair's acceleration.

As seen in Figure 10, the configuration of this study's pilot and flight-student VOR phase mean is comparable to other normative studies (Durney, 2016; Zalewski, 2017). However, the current study's mean phase lead was slightly greater at the lower frequency rotations than other comparable normative studies. This difference in low frequency phase, with the pilot and flight-student cohort expressing slightly higher phase leads than comparable non-pilot studies ((Durney, 2016; Zawleski, 2017) is likely the result of vestibular habituation (Ahn, Lee, Kim, & Lee, 2000; Aschan, 1954; Clément, Tilikete, & Courjon, 2008). The mid-frequency rotational stimuli of 0.16 and 0.32 produced a phase shift less than 0°, which suggests a near perfect temporal relationship for this frequency range, which again is to be as expected with an adult cohort with healthy, normal vestibular systems. Increased measures of phase lead at high rotational stimuli (i.e., 1.28 and 1.75 Hz) is common and a likely effect of VOG goggle dermal slip (i.e., goggles sliding on the skin of the head due to high accelerations), rather than a pathologic difference in function.

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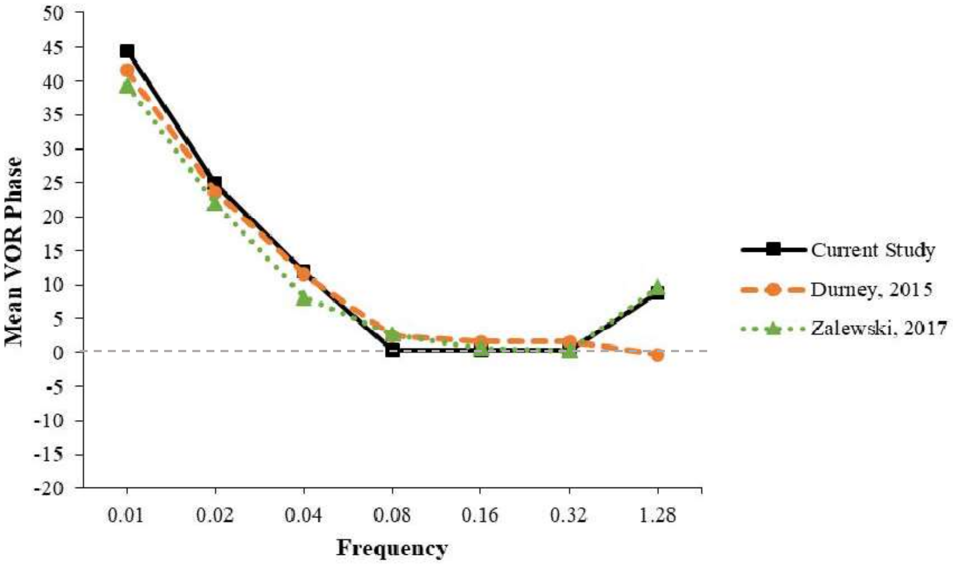

Figure 10. Mean VOR Phase Comparisons at Select Rotational Frequencies. Note. Comparative cohorts are publically available adult normative values, presumably non-military and non-pilot.

Asymmetry (also often referred to as symmetry) of the vestibular system identifies the sensitivity of the right and left peripheral vestibular components via the difference in percent VOR produced during rightward and leftward rotation. The current study cohort revealed a preponderance (i.e., preferential bias to rightward rotations) for all test frequencies from 0.01 to 0.64 Hz. Note in Table 4, the calculated SD for this range of rotational frequencies ranged from 8 to 16%. The percent symmetry measured in comparative normative standards (Figure 11) also display variable performance as indicated with large SD, with a mean symmetry closer to 0%.

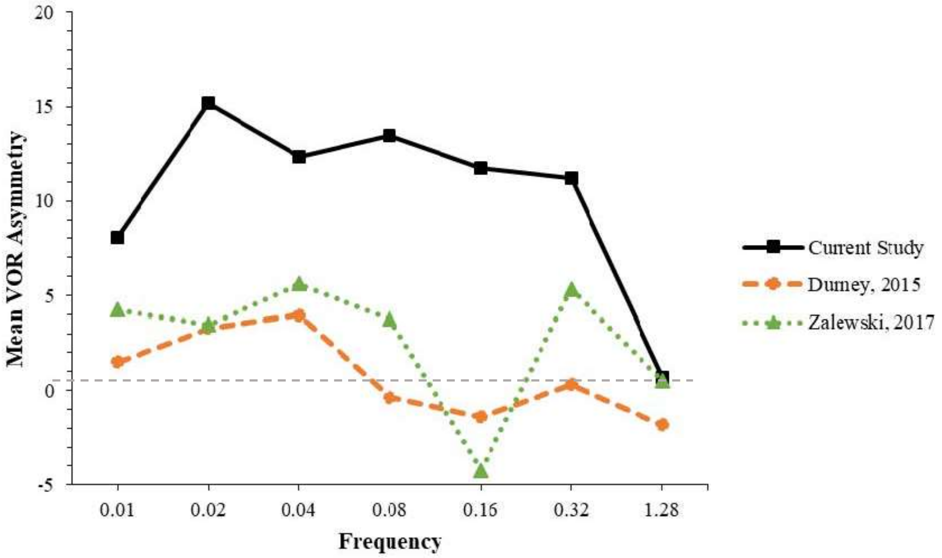

Figure 11. Mean VOR Asymmetry Comparisons at Select Rotational Frequencies. Note. Comparative cohorts are publically available adult normative values, presumably non-military and non-pilot.

VST

The outcome measure of interest for the VST is the time constant (TC), which is the rate at which the elicited VOR decays to 37% of its peak. The TC has been suggested to be a measure of velocity storage (Bos, Bles, & DeGraaf, 2002). This is completed under four test conditions: per-clockwise (i.e., rightward acceleration), post-clockwise (i.e., rightward deceleration), per-counter clockwise, and post-counterclockwise (Brey, McPherson, & Lynch, 2008b). The reported low frequency (i.e., 60°/sec) TC in a cohort of clinically normal adults is greater than or equal to 10 sec (Brey, McPherson, & Lynch, 2008a). Like the SHA phase variable, the TC value of the VST is consistent and reproducible and is not influenced by the participant's mental or arousal state (Maes et al., 2008).

While published studies of VST normative values do exist (Brey, McPherson, & Lynch, 2008b; Hoffer, et al., 2003; Maes et al., 2008; Schwarz & Henn, 1989), the recording parameters used vary, which reduces the generalization and ability to compare to the current study's findings. While not a normative study, a small control group (n = 4) of cohort of Marine Engineers not routinely exposed to low-level blasts were found to normal responses, i.e., a mean recorded TC exceeding 10 sec (Littlefield et al., 2016). As seen in figure 12, the results from the current study found mean TC for three of the four measures (i.e., per-CW, per-CCW, and post-CCW) to be less than 10 sec, suggesting that the nystagmus generated (i.e., the VOR) reduced faster than that of a population of clinically normal adults without flight experience. Bos, Bles, and DeGraaf (2002) reported that flight students (fixed- and rotary-wing) who were susceptible to motion sickness (i.e., airsickness) displayed an increased TC compared to flight students who were not susceptible to motion sickness. This finding would suggest that the pilot population is able to suppress VOR movement. Again, supporting Ahn's (2003) conclusion that VOR suppression may be an important ability for pilots while in flight.

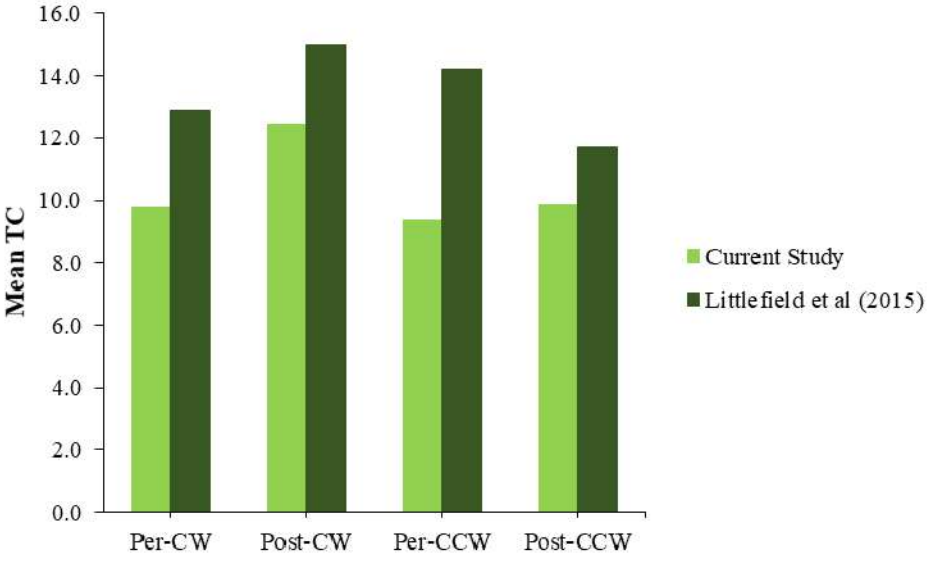

Figure 12. Comparison of 60°/sec Time Constants among Military Cohorts.

Like that of the SHA subtest, the participant's mental alertness can significantly affect both VOR gain and TC (Matta & Enticott, 2004; Zalewski, 2017). Participants were told of the importance in maintaining mental alertness at multiple times throughout the study (i.e., during the informed consent, and prior to the start of the test battery). During the subtest, participants were tasked with completing mathematical calculations and/or questions to aid in maintaining their alertness.

Visual-Vestibular Interaction Tests: Enhancement and Suppression

The assessment of the visual-vestibular interaction, including evaluation of the central vestibular system, is completed with the visual enhancement (VE) test and the visual suppression (VS) test. The VE subtest assesses the ability to increase the VOR gain due to visual-vestibular interaction. This subtest is often also called either the visual-vestibular ocular reflex or VVOR. The VE subtest measures the ability of the visual system to enhance the VOR due to whole body rotations like that in the SHA subtest. This works best for rotations below 1.0 Hz, as RC stimuli above that cutoff are subject to deterioration (Zalewski, 2017).

There is limited published information available that reports normative values of a clinically normal adult population. Casto, Nedostup, and Byrne (2012) provide results on multiple RC subtests for both Soldiers with and without blast induced TBI. Their control group was comprised of 26 Soldiers who did not have clinical symptoms consistent with TBI. We used these results as a comparative cohort for the current study results (Figure 13). The comparison between military cohorts (aviators compared to soldiers) suggest that the aviator cohort displays greater ability of enhancement, at least for the common test frequencies (0.08, 0.32, and 0.64). An example of use of the VVOR in action is tracking a stationary target while walking, driving, or turning (Zuma E Maia et al., 2015). This would be imperative for an aviator, but perhaps not so much for a ground Soldier. The aviator cohort of the current study was found to have a low mean VOR gain compared to other normative values of non-aviator cohorts. The Casto, Nedostup, and Byrne (2012) dataset does not provide the SHA mean VOR measures for comparison.

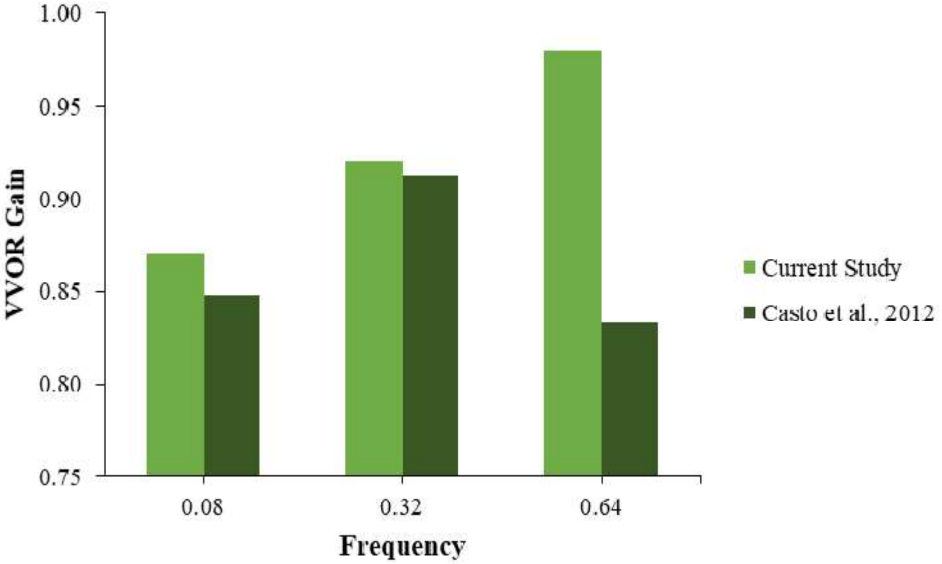

Figure 13. Comparison of Mean VVOR Gain among Military Personnel. Note. Casto, Nedostup, and Byrne's (2012) control cohort were 26 Soldiers without blast-induced TBI.

Visual suppression (VS) measures the participant's ability to suppress the VOR to keep a target image on the fovea of the retina (Jacobson, Piker, Do, McCaslin, & Hood, 2012). This test is also often referred to as the visual fixation suppression testing and visual-vestibular fixation. An example of an aviation operational maneuver that would require the ability to suppress the VOR is when a pilot is required to monitor a head mounted display during a turn (Zuma E Maia et al., 2015).

The suppressed VOR gain was then compared to available normative values utilizing military personnel with common test parameters (Casto, Nedostup, and Byrne, 2012). As seen in Figure 14, as the rotational frequency increased, the measured VOR gain also increased. This was an anticipated response, as it suggests that the central mechanisms responsible for suppressing the VOR are better at lower rotational frequencies than at the higher frequencies (Brey, McPherson, & Lynch, 2008a). As cited in Zalewski (2017), Goldberg et al. (2012) states that effective suppression can be anticipated up to 1.0 Hz. It is at this point (rotational frequencies $\geq$ 1.0 Hz) where the central mechanisms responsible for the VOR and associated eye movements (i.e., smooth pursuit pathway) become less effective. The amount of suppression measured varied by study. Of the common test frequencies between the current study and the Casto, Nedostup and Byrne (2012) study, a one-sample *t*-test revealed a significant difference on mean VOR suppression only at 0.32 Hz ($p = 0.03$, $t = -2.263$).

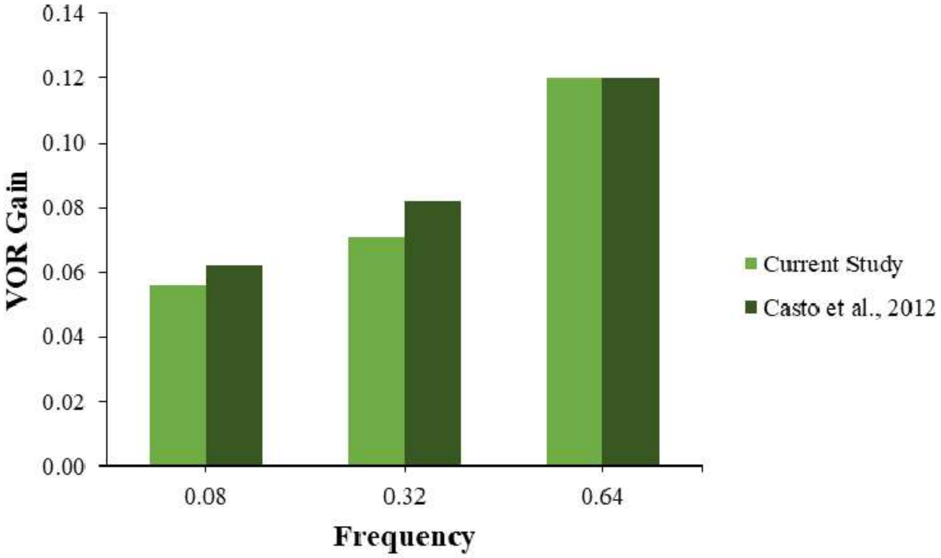

Figure 14. Comparison of VOR Gain Suppression. Note. Casto, Nedostup, and Byrne's (2012) control cohort were 26 Soldiers without blast-induced TBI.

Static SVV, Static SVH, and Dynamic SVV

The static SVV (sSVV) and sSVH subtests measure the otolith function (i.e., utricle) and central graviceptive pathways (Akin, Murnane, Pearson, Byrd, & Kelly, 2011; Ashish, Augustine, Tyagi, Lepcha, & Balraj, 2017; Pavlou, Wijnberg, Faldon, & Bronstein, 2003). These tests measure the participant's perception of verticality in relation to earth's gravitational planes (Tribukait & Eiken, 2012). Previous studies indicate the normative for the sSVV and the sSVH can range anywhere from ± 2.0° to ± 3.0° (Akin et al., 2011; Ashish, Augustine, Tyagi, Lepcha, & Balraj, 2016; Böhmer & Rickmann, 1994; Hafström et al., 2004), and that the SVV and SVH can be used interchangeably to measure the same function (Hafström et al., 2004).

The overall average from this cohort is in agreement with these findings, as the cohort M (SD) was -0.9° (1.7) from true vertical and -1.0° (1.6) from true horizontal. The statistical analysis of these subtests indicate a large variance (i.e., SD) in participant performance. When looking at individual variation, and using the most lax normative cutoff of ± 3.0° (Karlberg et al., 2002; Hafström et al., 2004), the percentage of outliers is 14% for the SVV and 9% for the SVH. This is somewhat unexpected as all participants denied history of visual or vestibular disorders, head injury or known other medical condition at the time of enrollment. Individual variances outside the published range of sSVV does not necessarily indicate a peripheral or central vestibular pathology. Asai et al. (2009) reported abnormal sSVV findings among a subclinical population of patients who experience migraine or tension type headaches (Asai et al., 2009). However, we did not inquire nor did any of the participants report any headaches at the time of data collection.

Dynamic measures of the SVV, or the UC-SVV, assesses individual utricular function during high velocity rotation. Testing occurs when the RC is in three positions: right, center, and left. In the right and left conditions, the chair translates or moves 3.85 cm off center while rotating. When the chair moves to the right, the left ear moves to the axis of rotation, and the right ear is stimulated. The reverse is true when the chair is offset 3.85 cm to the left. Limited information is available with regards to UC-SVV for any clinical population, let alone a healthy, asymptomatic population like that of military pilots.

Normalizing the UC-SVV score removes the baseline bias scores when the RC is static (i.e., sSVV), and provides a truer measure of individual utricular function (Akin et al., 2011; González, King, & Kiderman, 2014). The corrected (i.e., UC-SVV – sSVV) mean degree deviation for the three chair positions (right, center, and left) were: -2.8, -0.28, and 2.9°. These findings would suggest a symmetrical response to UC rotation and in agreement with reports by González, King, and Kiderman (2014) and Akin et al. (2011).

Responses from the UC-SVV subtest can also be completed by measuring direct physiologic stimulation of the utricles via torsional ocular counterroll (OCR). González, King, and Kiderman comment that use of the OCR clinically is “often problematic due to the minute nature of overall torsion and difficulties obtaining consistent recordings” (p. 254). As the focus of this report was for clinical application, OCR measures are not included. Rather, this report focuses on the perception of verticality (i.e., SVV) while in dynamic motion. Future studies should include measurement of the OCR.

crHIT

The crHIT provides repeated controlled high frequency (i.e., approximately 1000°/sec) whole-body rotations to measure unilateral hSCC function via measurement of the VOR. The crHIT was the most recent addition to the NOTC RC test battery, and was first described by Furman, Shirey, Roxberg, and Kiderman (2016). Limited published literature is available for review (Balaban et al., 2016; Furman et al., 2016) and comparison to the current study's results.

To the best of our knowledge, this is the first study to report on the crHIT among a cohort of clinically normal military aviators. However, use of the comparable video HIT or vHIT among military personnel with (i.e., fighter pilots) and without (i.e., soldiers) flight experience was completed by Zuma E Maia et al. (2015). The investigators noted a difference in VOR gain between the two groups was found for the left posterior SCC. Additionally, further evaluation into the effect of flight time on vestibular function found no significant difference in mean VOR gain among their active pilot cohort. The authors conclude that adaptation or habituation at high frequency stimulations in the active pilot population does not occur.

Unlike the Zuma E Maia et al. (2015) study that evaluates all six SCC, the current study only evaluated the right and left h-SCC. The average (average of rightward and leftward rotations) VOR gain was calculated using both the right and left impulse rotations. Unlike Zuma E Maia et al. (2015), a military control group of soldiers without flight experience was not utilized. Additionally, 55% of the current study (26 of 48) were pilots and flight students with 20 to 1000 flight hours. The Zuma E Maia et al. (2015) active pilot population were pilots with 1000 to 3000 flight hours. However, when you compare the current study cohort to the Zuma E Maia et al. (2015) active pilot cohort, one notes somewhat similar performances (Figure 15). Particularly the VOR gain measured for the left lateral (i.e., horizontal) SCC. These noted differences can possibly be attributed to the different equipment (although comparable), stimuli delivery mechanisms (manual rotation via clinician as in the vHIT versus computerized controlled with the crHIT), or sample size.

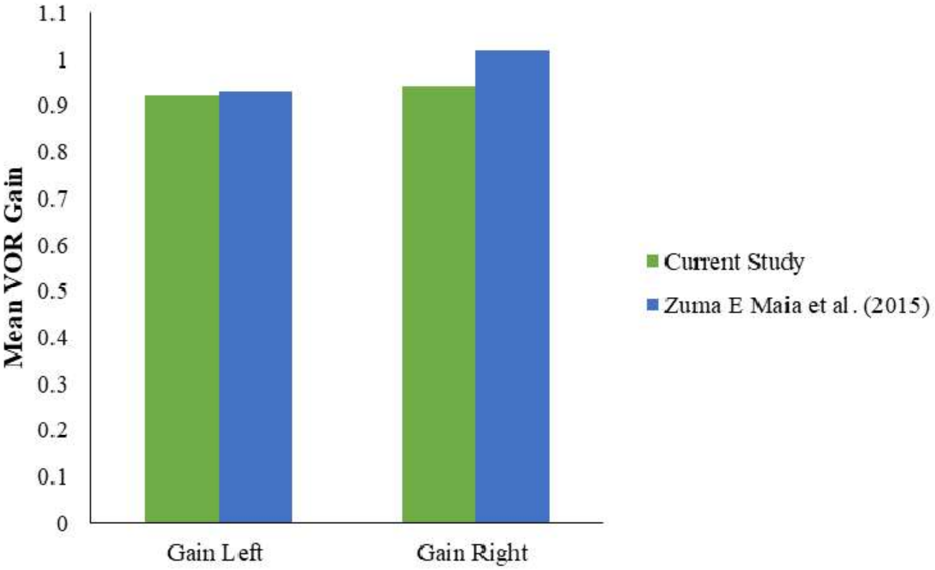

Figure 15. Comparison of Mean VOR Gain to Lateral High Frequency Impulses in Military Pilots. Note. Sample size and test paradigm differs between the two studies. Current study used the crHIT with a sample of 47 pilots and flight students, Zuma E Maia et al. (2015) used the vHIT with a sample of 20 active pilots.

As seen in Figure 16, the average crHIT VOR gain results from the current study was compared to a control cohort (non-military, non-aviator) reported by Furman et al., 2016. The control cohort used was comprised of 22 adults between the ages 24 to 64 years, who denied a history of either neurologic disease, otologic disease, and performed within normal limits on tests of audio-vestibular function (i.e., oculomotor testing, caloric testing). Using a one-sample *t* test, a statistically significant difference was found between the normative average gain (velocity) in the current study and Furman, Shirey, Roxberg, and Kiderman (2016), $p = 0.04$, $t = -2.109$. This would suggest that vestibular function as measured with the crHIT of the current study cohort is statistically different from that of a non-military, non-aviators normative cohort.

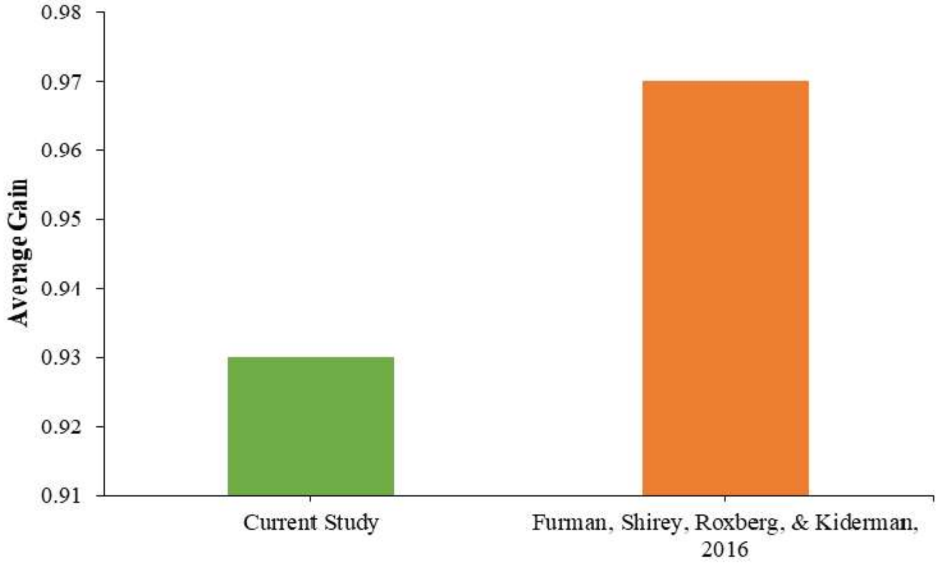

Figure 16. Comparison of crHIT Average VOR Gain.

According to Balaban et al. (2016), a positive history of mild TBI would result in a higher measure of asymmetry and a reduced average gain (statistically significant). The current study cohort was asked about history of head injury within six months of participation, not total history. Therefore, it may be possible that participants in the current study had experienced a head injury or TBI, and not revealed it to the study personnel within the demographic questionnaire. Another possible explanation for measured low gain is decreased attention and/or fatigue. In the order of tests, this was the second to last test completed, and therefore could be affected by reduced participant alertness. A final reason why a significant difference was noted from the Furman et al. (2016) cohort and not the Balaban et al. (2016) cohort may be due to the variance in participant responses. The measured SD for the average VOR gain was 0.03 (Furman et al., 2016) and 0.04 (Balaban, 2016), while the current study had a measured SD of 0.13.

Study Limitations

Exclusionary criteria was determined by self-report via demographic questionnaire. It is entirely possible that a participant withheld or failed to disclose an injury or issue that would disqualify them from participating. Such exclusionary criteria includes history of blast exposure or TBI. Further, a second source (i.e., electronic medical record or flight surgeon) was not consulted to verify qualification for each participant. Another limitation exists with regards to the study design. This was a descriptive study, and not hypothesis driven. Therefore, a control group (i.e., military non-aviators) was not utilized. Therefore, no comments can be made regarding the difference in vestibular function between military aviators and military non-aviators.

Gender was not controlled for in this study. The majority of participants, that is 48 of 49 (98%), were male. As cited in Curry, Kelly, Gaydos (2018), approximately 5.2% of Army aviators are female, while the current study's female population was 2%. Thus, the male to female ratio of participants in this study is not truly representative of Army aviation as a whole. That being said, the role that gender plays in the production and mitigation of the VOR is debatable. The SHA test does not seem to be influenced by gender (Maes et al., 2008; Durney, 2016; Li, Hooper & Cousins, 1991), while the Pseudo Randomized Rotation Test (Maes et al., 2008) does. Maes et al. (2008) therefore recommended the development and use of gender-specific normative values. The relationship of gender, flight experience and vestibular function has yet to be thoroughly investigated, and therefore could be explored in future studies.

Participant auditory function was neither a measured variable, nor a variable for which we controlled. Participants were asked via the demographic questionnaire if they had been diagnosed with a condition that affects their hearing or balance system, but not if they had been diagnosed with a hearing loss. Additionally, the current study protocol did not include an audiometric evaluation. Shupak, et al. (1994) found a statistically significant difference in VOR gain between military personnel diagnosed with noise induced hearing loss and with normal hearing. Due to the nature of the participant's occupations (i.e., military rotary-wing pilot or flight student), it can safely be assumed that these individuals are exposed to hazardous noise levels on the job. However, with appropriate use of occupational personal protection equipment (i.e., helmet with communications earplugs), these hazards should be mitigated. That being said, we cannot rule out the possibility of noise induced hearing loss among this study cohort.

Conclusions and Recommendations

The current study provides evidence that vestibular function in aviators versus non-aviators is different and may represent habituation to forces and stimuli experienced while in flight. These findings suggest that job specific vestibular normative standards may be needed when the standards for non-aviators reveal normal function, despite complaints of imbalance and dizziness by the aviator. Considering the implication on job performance, future research should focus on the duration of long-term habituation retention with respect to periods when an aviator is no longer flying routinely. Other significant areas that need development and that would be applicable to performance for aviators would be identifying the correlation between aviation specialties and the vestibular changes that may result from exposure to these specific stimuli. More research on which tests and subtests are most relevant for aviators would further the development of a normative standard. For example, the SHA subtest is one such test that evaluates VOR function over a wide range of test frequencies. However, natural head movement typically ranges between 0.5 to 8 Hz (Shupak et al., 2001). Therefore, RC testing that utilize low frequency rotational stimuli may not necessarily be representative of "the level of performance required during the extreme acceleration and velocities encountered in flight" (Shupak et al., 2003, p. 320). High frequency rotational stimuli should therefore be included in the evaluation of aviators.

Lastly, further exploration into the association between vestibular function and motion sickness susceptibility, particularly in prospective pilots or flight students is needed and may be obtainable by more studies involving the SHA test. Gordon et al. (1995) demonstrated the use of the SHA test to differentiate between military personnel who are and are not susceptible to seasickness (i.e., motion sickness). That is, a significant difference in SHA VOR gain and phase was noted, with the susceptible cohort expressing higher gain and lower phase lead at lower rotational frequencies. While individual variances exist and Gordon et al. (1995) suggest that the SHA should not be used to definitively categorize motion sickness susceptibility, the SHA may be used to predict performance.

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