JARO: 207–214 (2021)
DOI: 10.1007/s10162-020-00780-1

JARO
Journal of the Association for Research in Otolaryngology

Research Article

Self-Reported Sense of Direction and Vestibular Function in the Baltimore Longitudinal Study of Aging (BLSA)

PRIYAL GANDHI,[1] KEVIN BIJU,[1] BROOKE N. KLATT,[2] ELEANOR SIMONSICK,[3] AND YURI AGRAWAL[2]

[1]*Johns Hopkins University School of Medicine, Baltimore, MD 21205, USA*

[2]*Department of Otolaryngology-Head and Neck Surgery, Division of Otology, Neurotology, and Skull Base Surgery, Johns Hopkins University, Baltimore, MD 21205, USA*

[3]*National Institute on Aging, National Institutes of Health, Baltimore, MD 21225, USA*

Received: 14 January 2020; Accepted: 8 December 2020; Online publication: 15 January 2021

ABSTRACT

Sense of direction is an individual's ability to navigate within an environment and generate a mental map of novel environments. Although sense of direction is correlated with psychometric tests of spatial ability, it also reflects an individual's real-world spatial ability that is not fully captured by laboratory-based assessments. Sense of direction is known to vary widely in the population and has been shown to decline with age. However, other factors that contribute to an individual's sense of direction have not been well-characterized. Vestibular impairment has been linked to reduced spatial cognitive ability, which encompasses spatial memory and navigation skills. Several studies have shown that vestibular input is necessary for effective spatial cognition, notably accurate spatial navigation ability. These studies have typically considered laboratory-based spatial navigation assessments; however, the influence of vestibular function on variation in real-world sense of direction is unknown. In this study, we evaluated whether vestibular function is associated with self-reported sense of direction. Participants for this cross-sectional study were recruited from the Baltimore Longitudinal Study of Aging, a longstanding cohort study of healthy aging. In a modified version of the Santa Barbara Sense-of-Direction (SBSOD) Scale, participants rated statements about spatial and navigational abilities. A lower average score indicates poorer self-reported sense of direction. Vestibular function testing included cervical vestibular-evoked myogenic potential (VEMP) to assess saccular function, ocular VEMP to assess utricular function, and the video head-impulse test to assess semicircular canal function based on vestibular ocular reflex. The study sample included 82 participants with mean age of 71.0 (± 16.9) years and mean SBSOD score of 4.95(± 1.07). In a multivariate linear regression model, female sex and bilateral saccular loss were associated with a lower average SBSOD score. These data suggest that vestibular impairment contributes to the known variation in spatial navigation ability.

Keywords: Spatial navigation ability, Spatial cognition, Saccular function

INTRODUCTION

Sense of direction is an individual's ability to navigate within an environment and learn the layout of new environments (Wolbers and Hegarty 2010). Sense of direction reflects an individual's environmental spatial ability in the real world. Classic written or computer-based tests of spatial ability conducted in the laboratory have been shown to lack ecological validity in capturing environmental sense of direction ability. In contrast, assessments of sense of direction based on self-report have been found to be better predictors of performance on real-world environmental spatial tasks (Hegarty et al. 2002; Kozlowski and Bryant 1977).

Sense of direction ability in the real-world is known to vary widely across individuals (Evans 1980); however, the main drivers of this inter-individual variability

Correspondence to: Priyal Gandhi · Johns Hopkins University School of Medicine · Baltimore, MD 21205, USA. email: pgandhi5@jhmi.edu

have not been well-characterized (Sholl et al. 2006). Sense of direction is known to decline with age (Lester et al. 2017); although it is unclear whether age-related decline in cognitive, sensory, and/or other characteristics contribute to decline in sense of direction with age. Several animal and human studies have shown that vestibular input is necessary for effective performance on spatial cognitive tests, such as tests of spatial memory and spatial navigation ability (Xie et al. 2017; Glasauer et al. 2002; Bigelow et al. 2015). These studies have typically considered laboratory-based spatial navigation tests; however, the influence of vestibular function on real-world sense of direction ability is unknown.

In this study, we evaluated the relationship between vestibular function and self-reported sense of direction in a cohort of healthy adults from the Baltimore Longitudinal Study of Aging. Self-reported sense of direction ability was measured using the Santa Barbara Sense of Direction (SBSOD) Scale, a 15-item self-report measure of people's judgments about their environmental spatial abilities (Hegarty et al. 2002). Previous analysis of the SBSOD scale has shown that a modified, abbreviated version can be used with little reduction in reliability (Condon et al. 2015); thus, the shortened form was used in this study. We report in this study that vestibular function contributes to the known variation in sense of direction ability in adults.

METHODS

Participants

Participants for this cross-sectional study were recruited from the Baltimore Longitudinal Study of Aging (BLSA), a longstanding cohort study of healthy aging supported by the Intramural Research Program of the National Institute on Aging. The study currently has over 1300 healthy participants ages 20 and older that meet a series of predetermined criteria ("BLSA History" 2019). Eligible participants for this cross-sectional study completed both the modified self-reported Santa Barbara Sense-of-Direction (SBSOD) questionnaire and vestibular function testing during the same BLSA study visit. Additional vision, hearing, and cognitive metrics were also assessed, including visual acuity, contrast sensitivity, stereoacuity, visual fields, auditory 4-frequency tone perception, Card Rotation Test score, and Triangle Completion Test performance. Written informed consent was obtained from all participants, and the BLSA study protocol was approved by the National Institute of Environmental Health Sciences Institutional Review Board.

Self-Reported Sense of Direction

The SBSOD scale has a test–retest reliability of .91 and moderate correlations with multiple behavioral navigation tasks, demonstrating construct validity (Hegarty et al. 2002). Although the original SBSOD scale includes 15 statements, Condon et al. (2015) demonstrated that a shorter version of the scale reliably predicts participants' self-reported sense of direction. The modified version of the SBSOD Scale includes seven statements about spatial and navigational abilities rated on a scale of 1 to 7, with a higher score indicating better ability. These statements are "I am very good at judging distances"; "I have a very good sense of direction"; "I very easily get lost in a new city" (R); "I have trouble understanding directions" (R); "I don't remember routes very well while riding as a passenger in a car" (R); "I can usually remember a new route after I have travelled it only once"; and "I don't have a very good mental map of my environment" (R). An (R) indicates statements that are reverse scored. A lower average composite score of the seven statements indicates lower self-reported sense of direction.

Vestibular Function Testing

Vestibular function testing consisted of the cervical vestibular-evoked myogenic potential (cVEMP) to assess saccular function, the ocular VEMP (oVEMP) to assess utricular function, and the video head-impulse test (vHIT) to assess semicircular canal function based on vestibular ocular reflex (VOR). Testing procedures are described in detail in previously published work (Li et al. 2014; Nguyen et al. 2010; Harun et al. 2016; Li et al. 2015a; Schneider et al. 2009; Weber et al. 2009; Li et al. 2015b), and are discussed briefly below.

Vestibular-Evoked Myogenic Potentials (VEMP)

Both cVEMP and oVEMP were recorded using a commercial electromyographic system (software version 14.1, Carefusion Synergy, Dublin, OH) (Li et al. 2014; Nguyen et al. 2010). Disposable, pregelled Ag/AgCl electrodes with 40-in safety lead wires from GN Otometrics (Schaumburg, IL) were used to record electromyogram signals. These signals were band-pass filtered and amplified using 20 to 2000 Hz for cVEMP and 3 to 500 Hz for oVEMP.

Cervical Vestibular-Evoked Myogenic Potentials (cVEMP)

To measure saccular function, the cVEMP test uses sound to evoke cervical myogenic potentials. A trained examiner placed electromyographic electrodes bilaterally on the sternocleidomastoid muscle and sternoclavicular junction of the study participant who sat on a chair at a 30-degree incline (Li et al. 2014; Nguyen et al. 2010; Harun et al. 2016; Li et al. 2015a). A ground electrode was placed on the manubrium. Headphones (VIASYS Healthcare, Madison, WI) were used to deliver sound stimuli monaurally with 500 Hz and 125 dB tone bursts. Presence or absence of a myogenic potential response was recorded as per previously published guidelines (Li et al. 2015a; Nguyen et al. 2010).

Ocular Vestibular-Evoked Myogenic Potentials (oVEMP)

To measure utricular function, the oVEMP test uses vibration to evoke ocular myogenic potentials. A trained examiner placed a noninverting electrode on the cheek inferior to the pupil approximately 3 mm below the orbit (Li et al. 2014; Nguyen et al. 2010; Harun et al. 2016) of the study participant who sat on a chair at a 30-degree incline (Li et al. 2014; Nguyen et al. 2010; Harun et al. 2016; Li et al. 2015a). The examiner placed another inverting electrode 2 cm below the noninverting electrode and a ground electrode on the manubrium. Prior to testing, confirmation of symmetric bilateral signals was obtained by asking the participant to perform several 20-degree vertical saccades. If bilateral signals had more than 25 % asymmetry, new electrodes were applied. Throughout the duration of oVEMP testing, the participant was asked to continue a 20-degree upgaze, while a reflex hammer (Aesculap model ACO12C, Center Valley, PA) was used to perform head taps in the midline of the face at the hairline, approximately one-third of the space between the inion and nasion. Presence or absence of a myogenic potential response was recorded as per previously published guidelines (Li et al. 2015a; Nguyen et al. 2010).

Video Head Impulse Testing (vHIT)

As a measure of semicircular canal function, horizontal vestibular-ocular reflex (VOR) was assessed using the vHIT (Harun et al. 2016). To detect VOR gain, the EyeSeeCam system (Interacoustics, Eden Prarie, MN) was used in the same plane as the right and left horizontal semicircular canals (Schneider et al. 2009). The horizontal canals were placed in the correct plane of stimulation by slanting the participant's head down 30° from the horizontal axis. Throughout the duration of testing, the participant was asked to fix their gaze on a wall target 1.5 m away. For at least 10 times toward the right side and at least 10 times toward the left side, the participant's head was moved 5 to 15° at high speed (approximately 150–250° per second). The direction of head movement was randomized to maintain unpredictability. Measurement of eye and head velocity by the EyeSeeCam system was used to calculate the VOR gain by dividing the eye velocity by the head velocity. As normal eye and head velocities should be equal, a normal VOR gain should equal 1.0.

Analyses

Descriptive statistics including participant demographics, self-reported sense of direction, and vestibular function testing were analyzed. Multivariate linear regression models adjusting for participant demographics (age, sex, and years of education) and Mini Mental Status Exam (MMSE) score (Folstein et al. 1975) were also conducted to investigate the relationship between vestibular function and self-reported sense of direction. Assumptions for multivariate linear regression analysis were verified. Quantiles of dependent variables of interest were plotted against quantiles of normal distribution to evaluate for normality. There was no evidence of multicollinearity or homoscedasticity. Further, previous work has shown low correlation between age and the SBSOD Scale, and no correlation between tests of cognitive ability and the SBSOD Scale (Condon et al. 2015). Scatter plots revealed reasonably linear relationships between dependent and independent variables, supporting the use of linear regression models. Statistical analyses were conducted using STATA 15.1 (College Station, TX).

RESULTS

Participant demographics and descriptive statistics of clinical testing variables are shown in Table 1. The study sample included 82 participants with mean age of 71.0 (± 16.9) years and mean SBSOD score of 4.95(± 1.07). Of the 74 participants who completed saccular function testing, 13 (17.6 %) had unilateral saccular loss of function, and 3 (4.0 %) had bilateral saccular loss of function. Among 75 participants who completed utricular function testing, 4 (5.3 %) had unilateral loss of utricular function and 2 (2.7 %) had bilateral loss of utricular function. Seventy participants completed semicircular canal function testing with a mean VOR gain of 1.00(± 0.15).

In a multivariate linear regression model adjusted for age, MMSE score, years of education, and saccular function, men demonstrated higher average SBSOD score (β = 0.93, 95% CI 0.21, 1.65) than women (Table 2). Additionally, in a multivariate linear

TABLE 1

Demographic Characteristics and Clinical Test Results of Study Population ($n = 82$)

Demographics and clinical testing	*Mean(± SD)*	*N (%)*
Age (years)	71.0 (± 16.9)	
Sex		
Female		42 (51 %)
Male		40 (49 %)
Mini Mental Status Exam (MMSE) score[1]	28.2 (± 1.4)	
Education (years)[2]	17.1 (± 2.3)	
Santa Barbara Sense-of-Direction Scale score	4.95 (± 1.09)	
Saccular function[3]		
Normal function		58 (78.4 %)
Unilateral loss		13 (17.6 %)
Bilateral loss		3 (4.1 %)
Utricular function[4]		
Normal function		69 (92 %)
Unilateral loss		4 (5.3 %)
Bilateral loss		2 (2.7 %)
Vestibulo-ocular reflex (VOR) mean[5]	1.00 (± 0.15)	

[1]MMSE score was out of a maximum of 30 points; data were missing for 24 participants

[2]Data were missing for 4 participants

[3]Data were missing for 8 participants

[4]Data were missing for 7 participants

[5]Data were missing for 12 participants

regression model adjusted for age, sex, MMSE score, and years of education, persons with bilateral saccular loss had a lower average SBSOD score ($\beta = -1.66$, 95 % CI −3.15, −0.17) than those with normal saccular function (Table 2). Examining each item on the SBSOD as a separate outcome, we observed that the following items were associated with bilateral saccular loss: "I am very good at judging distances" ($\beta = -2.95$, 95% CI −4.84, −1.06); "I have a very good sense of direction" ($\beta = -2.89$, 95% CI −4.95, −0.83); and "I can usually remember a new route after I have travelled it only once" ($\beta = -3.34$, 95% CI −5.64, −1.04). Presence of utricular function and VOR mean gain were not associated with self-reported sense of direction in multivariate regression models (Tables 3, 4). Multivariate regression of multiple vision parameters (including visual acuity, contrast sensitivity, stereoacuity and visual fields) and hearing ability (4-frequency tone perception) with SBSOD score revealed no significant relationships, but greater distance traveled on the Triangle Completion Test (TCT) was associated with lower average SBSOD score ($\beta = -0.01$, 95% CI −0.02, 0) (Table 5).

DISCUSSION

In this cross-sectional study of healthy adults, we observed that bilateral saccular impairment was significantly associated with poorer self-reported sense of direction. Self-reported sense of direction aims to assess how people orient themselves in an environment and

TABLE 2

Impact of presence of saccular function on self-reported sense of direction ($n = 52$)

Characteristic	**β (95 % CI)**
Age (years)	−0.02 (−0.06, 0.02)
Sex	
Female	Reference
Male	**0.93 (0.21, 1.65)**
Mini Mental Status Exam (MMSE) score[1]	0.06 (−0.18, 0.31)
Education (years)	0.00 (−0.13, 0.14)
Saccular function	
Normal function ($n = 41$)	Reference
Unilateral saccular loss (n = 8)	−0.19 (−1.11, 0.74)
Bilateral saccular loss ($n = 3$)	**−1.66 (−3.15, −0.17)**

[1]MMSE score was out of a maximum of 30 points

Significant associations ($p < 0.05$) are bolded

TABLE 3

Impact of presence of utricular function on self-reported sense of direction ($n = 53$)

Characteristic	*β (95 % CI)*
Age (years)	−0.02 (−0.06, 0.02)
Sex	
Female	Reference
Male	0.62 (−0.12, 1.37)
Mini Mental Status Exam (MMSE) score[1]	0.02 (−0.23, 0.27)
Education (years)	0.02 (−0.12, 0.15)
Utricular function	
Normal function ($n = 50$)	Reference
Unilateral utricular loss ($n = 2$)	1.52 (−0.22, 3.26)
Bilateral utricular loss ($n = 1$)	0.10 (−1.62, 1.82)

[1]MMSE score was out of a maximum of 30 points

utilize spatial knowledge. Sense of direction is positively correlated with behavioral navigational task performance (Burte et al. 2018), though it captures an additional dimension which is an individual's global sense of direction ability in everyday life. Prior work has shown that sense of direction ability varies substantially in the population, with age and sex being the best characterized predictors of sense of direction ability. Our findings suggest that vestibular function also predicts sense of direction ability. Specifically, we found that impairment of the saccule was associated with reduced sense of direction ability. While our sample included a limited number of patients (3) with bilateral deficits in saccular function, we also analyzed performance on the Triangle Completion Test (TCT), an objective measure of spatial orientation and navigation. Previously, we demonstrated that saccular impairment and abnormal VOR gain were associated with poorer performance on the Triangle Completion Test (Xie et al. 2017). Notably, multivariate analyses in our sample of healthy adults revealed that poorer TCT performance (greater distance traveled) predicted lower self-reported navigation ability, suggesting an important link between these variables and underlying vestibular function.

In the current study, saccular function was the only vestibular variable found to be associated with self-reported sense of direction. The findings are consistent with previous work examining the unique relation of saccular function and spatial cognition. As the saccule is responsible for detecting the orientation of the head with respect to gravity, it is suggested to serve a unique role in encoding direction and spatial orientation (Nguyen et al. 2010; Li et al. 2014). In animal studies, mice with bilateral saccular loss performed more poorly on spatial navigation tasks than control mice (Yoder and Kirby 2014; Yoder et al. 2015). Additionally, rats placed in hypergravity to distort saccular function consequently had impaired spatial memory (Horii et al. 2017).

Spatial navigation is thought to occur via at least two different strategies: (1) route-based navigation, whereby individuals navigate a route based on a sequence of movements; and (2) place-based navigation, whereby individuals navigate based on a mental representation of the environment. Place-based navigation can further be divided into graph-based navigation, which involves relative locations of places, and survey-based navigation, which involves metric knowledge of the environment (Tolman 1948; Zhong and Moffat 2018). The hippocampus, which is involved in encoding spatial memory, is thought to have a specific response to saccular input (Smith, 2019). We previously observed an association between higher cVEMP amplitude and greater mean hippocampal volume in healthy adults (Kamil et al. 2018). Consis-

TABLE 4

Impact of vestibulo-ocular reflex (VOR) mean on self-reported sense of direction ($n = 53$)

Characteristic	*β (95 % CI)*
Age (years)	−0.03 (−0.07, 0.01)
Sex	
Female	Reference
Male	0.72 (−0.04, 1.49)
Mini Mental Status Exam (MMSE) score[1]	−0.01 (−0.27, 0.26)
Education (years)	−0.02 (−0.16, 0.13)
Vestibulo-ocular Reflex mean	−0.49 (−2.70, 1.72)

[1]MMSE score was out of a maximum of 30 points

TABLE 5

Impact of sensorimotor and cognitive tests on self-reported sense of direction ($n = 73$)

Characteristic	*β (95 % CI)**
Log10 (minimum angle resolution) uncorrected eye	−0.07 (−0.32, 0.18)
Uncorrected better eye worse than 20/40	0.02 (−0.70, 0.74)
Contrast sensitivity	0.13 (−0.12, 0.38)
Impaired stereoacuity	−0.05 (−0.75, 0.65)
Impaired visual field	1.28 (−0.83, 3.40)
Worse ear 4-frequency impaired (any)	0.01 (−0.71, 0.72)
Worse ear 4-frequency impaired (mild)	−0.18 (−0.96, 0.61)
Worse ear 4-frequency impaired (moderate)	0.06 (−0.79, 0.90)
Card Rotations Test Score	0 (0, 0.01)
Triangle completion test—angle of deviation	0.02 (−0.02, 0.06)
Triangle completion test—distance traveled	−0.01 (−0.02, 0)

*Multivariate regression adjusted for age, sex, Mini Mental Status Exam score, and education (years)

tent with these findings, better self-reported sense of direction has also been correlated with larger hippocampal volume (Burte et al. 2018) and greater communication strength between brain regions involved in visual path integration during spatial navigation tasks (Zajac et al. 2019). Additionally, we found in previous work that saccular impairment in patients with mild cognitive impairment and Alzheimer's disease is associated with driving difficulty (Wei et al. 2017) and poorer performance on spatial cognitive testing (Wei et al. 2018).

Whether saccular function is related to both route- and place-based navigation is unknown, so we performed an item-by-item consideration of the modified Santa Barbara Sense of Direction Scale. We found that several items were significantly associated with saccular function, suggesting key links between saccular function and spatial navigation strategy. A lower self-reported score on "I have a very good sense of direction" was associated with poorer saccular function, which parallels overall findings on the composite score of self-reported sense of direction. This item suggests that vestibular function contributes to generating a mental map, which is part of place-based navigation. Lower self-reported scores on the item "I am very good at judging distances" were also associated with poorer saccular function, supporting a contribution of vestibular function to place-based survey navigation. This finding corroborates previous research demonstrating that vestibular loss is associated with poorer performance on mental scanning tasks, which includes the mental processing of physical distances (Péruch et al. 2011). We also found that lower self-reported scores on the item "I can usually remember a new route after I have travelled it only once" were associated with bilateral saccular loss. This result augments findings from a longitudinal study by Ishikawa and Montello assessing individuals' spatial knowledge of a new route, which demonstrated that many individuals possess accurate spatial knowledge after one exposure to a new route, while others never obtain accurate spatial representations after multiple exposures to a new route (2006). This item could reflect either route- or place-based navigation ability and highlights a need to further explore the contribution of vestibular function to different types of spatial navigation. Altogether, these findings suggest that differences in saccular sensitivity may contribute to inter-individual variation in sense of direction ability and differential use of spatial navigation strategy.

The most frequent patient-reported metrics used in patients with vestibular disorders are the Dizziness Handicap Inventory (DHI), the Vertigo Symptom Scale (VSS), and the Vestibular Disorders Activities of Daily Living (VADL) scales (Fong et al. 2015; Jacobsen and Newman 1990; Yardley et al. 1992; Cohen and Kimball 2000). For the most part, these metrics have focused on dizziness and balance symptoms associated with impairment of vestibulo-ocular and vestibulo-spinal reflex function. The VADL scale includes 2 items that potentially tap into spatial navigation ability, including "Driving a car" and "Traveling around the community (car, bus)." As future studies provide further insight into the impact of vestibular impairment on the different types of navigation skills, the ability of the VADL, SBSOD, and/or new scales to capture vestibular-related navigation skills will need to be determined.

Limitations of this study include the cross-sectional design, which limits conclusions regarding causality. Moreover, our cohort of healthy individuals contributed to the limited variation in saccular, utricular, and semicircular canal function. Additionally, considering dichotomous vestibular function outcomes of present versus absent VEMP responses limited our analysis of VEMP responses, although doing so for an initial analysis on this subject allowed us to keep our entire sample of participants who underwent vestibular testing. Future studies should examine how outcomes compare in a larger study population and populations with known vestibular or cognitive deficits.

The results of this study show that self-reported sense of direction appears to be associated with vestibular function, further corroborating a growing body of evidence that suggests vestibular function contributes to spatial cognitive ability. Future work is needed to investigate whether vestibular impairment is causally related to reduce sense of direction, and what may be the mechanism for this link.

ACKNOWLEDGMENTS

We would like to acknowledge support for the statistical analysis from the National Center for Research Resources and the National Center for Advancing Translational Sciences (NCATS) of the National Institutes of Health through Grant Number 1UL1TR001079.

Funding Dr. Yuri Agrawal is receiving grant funding from NIA (#RO1 AG057667), NIH/NIDCD (#R03 DC015583), and NIH/NIDCD (#K23 DC013056). Priyal Gandhi was also a participant in the Medical Student Training in Aging Research (MSTAR) Summer Program, which was funded by NIA (#2T35AG026758).

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