Vestibular Perceptual Thresholds in Older Adults With and Without Age-related Hearing Loss

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Objectives: Older adults with age-related hearing loss (ARHL) are at greater risk of falling and have greater mobility problems than older adults with normal hearing (NH). The underlying cause of these associations remains unclear. One possible reason is that age-related declines in the vestibular system could parallel those observed in the auditory system within the same individuals. Here, we compare the sensitivity of vestibular perceptual abilities (psychophysics), vestibular end-organ functioning (vestibular evoked myogenic potentials and video head impulse tests), and standing balance (posturography) in healthy older adults with and without ARHL.

Design: A total of 46 community-dwelling older adults, 23 with ARHL and 23 with NH, were passively translated in heave (up and down) and rotated in pitch (tilted forward and backward) in the dark using a motion platform. Using an adaptive staircase psychophysical procedure, participants' heave and pitch detection and discrimination thresholds were determined. In a posturography task, participants' center of pressure (COP) path length was measured as they stood on a forceplate with eyes open and closed, on firm and compliant surfaces, with and without sound suppression. Baseline motor, cognitive, and sensory functioning, including vestibular end-organ function, were measured.

Results: Individuals with ARHL were less sensitive at discriminating pitch movements compared to older adults with NH. Poorer self-reported hearing abilities were also associated with poorer pitch discrimination. In addition to pitch discrimination thresholds, lower pitch detection thresholds were significantly associated with hearing loss in the low-frequency range. Less stable standing balance was significantly associated with poorer vestibular perceptual sensitivity.

Discussion: These findings provide evidence for an association between ARHL and reduced vestibular perceptual sensitivity.

Key words: auditory, self-motion, aging, posture, thresholds, rotation, translation.

List of Abbreviations: ABC = Activities-specific Balance Confidence; AP = Anterior-Posterior; ARHL = Age-related hearing loss; CEAL = Challenging Environment Assessment Laboratory; COP = Centre of pressure; ECC = Eyes Closed, Compliant Surface; ECSS = Eyes Closed, with Sound Suppression on a Compliant Surface; EOC = Eyes Open, Compliant Surface; EOF = Eyes Open, Firm Surface; HL = Hearing loss; IOI-HA = International Outcome Inventory for Hearing Aids; ML = Medial-Lateral; MoCA = Montreal Cognitive Assessment; NH = Normal Hearing; PEST = Parametric Estimation by Sequential Testing; PTA = Pure-tone average; SSQ = Speech, Spatial, and Qualities of Hearing Scale; VEMP = Vestibular-evoked myogenic potentials; cVEMP = Cervical vestibular-evoked myogenic potentials; oVEMP = Ocular vestibular-evoked myogenic potentials; vHIT = Video head impulse test; VOR = Vestibulo-ocular reflex.

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INTRODUCTION

In recent years, accumulating evidence from epidemiological studies on aging has revealed an important association between age-related hearing loss (ARHL) and an increased risk of mobility-related problems including walking difficulties, slower gait speed, loss of balance, and falls (Viljanen et al. 2009; Lin et al. 2011; Lin & Ferrucci 2012; Li et al. 2013; Chen et al. 2015; Jiam et al. 2016; Agmon et al. 2017; Campos et al. 2018). For example, older adults with hearing loss (HL) have been shown to be at three times greater risk of falling than older adults with normal hearing (NH) (Viljanen et al. 2009; Lin & Ferrucci 2012), and this risk increases by an additional 30 to 50% for every additional 10 dB HL (Lin & Ferrucci 2012). Falls are the single greatest cause of both fatal and nonfatal injuries in older adults (Center for Disease Control and Prevention 2018a, b) and HL affects over one in three older adults (National Institute on Deafness and Other Communication Disorders 2018). It is therefore important to better understand the nature of these associations, especially in light of the rapidly aging global population (United Nations 2015) and in an effort to inform interventions aimed at decreasing the risk of injury in older adults.

While the mechanisms underlying the associations between HL and mobility problems are largely unknown, a number of hypotheses have been offered including the possibility that HL: (1) increases cognitive load, which limits cognitive resources available to support mobility (Lin & Ferrucci 2012; Lau et al. 2016; Carr et al. 2019, 2020; Nieborowska et al. 2019), (2) restricts access to spatially relevant auditory cues that support orientation (e.g., Gago et al. 2015; Vitkovic et al. 2016; Negahban et al. 2017; Kowalewski et al. 2018), (3) causes social isolation leading to physical or cognitive deconditioning (Weinstein & Ventry 1982; Mick & Pichora-Fuller 2016; Robins et al. 2018), and (4) is associated with parallel declines in vestibular functioning (Viljanen et al. 2009; Lin & Ferrucci 2012; Campos et al. 2018). Several of these hypotheses have been previously evaluated experimentally; however, few studies have evaluated this last hypothesis.

The primary focus of the present study is to investigate the association between vestibular decline and ARHL. The auditory system and vestibular system have similar phylogenetic and developmental trajectories. They are located within close physical proximity to each other, have several mechanistic similarities (e.g., hair cells, stereocilium mechanoreceptors, vasculature,

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potassium-rich endolymphatic fluid) many of which show similar trajectories of loss with aging (e.g., Velázquez-Villaseñor et al. 2000; Rauch et al. 2001) and have shared peripheral innervation through the eighth cranial vestibulocochlear nerve. Here, we evaluate measurable associations between ARHL and, (a) vestibular *peripheral* end-organ functioning, specifically otolithic function as assessed by vestibular evoked myogenic potentials (VEMPs) and horizontal canal function measured by video head impulse tests (vHIT), (b) vestibular-mediated *behaviors* (i.e., standing balance) assessed by posturography tests, and (c) vestibular *perception* assessed by detection and discrimination thresholds.

AGE-RELATED HEARING LOSS AND THE PERIPHERAL VESTIBULAR SYSTEM

Methods that are often used to evaluate the functioning of the vestibular end-organs, specifically the otoliths (saccule and utricle) and semicircular canals, include cervical VEMP (cVEMP), ocular VEMP (oVEMP), and vHIT, respectively. Importantly, these tests are both measures of vestibular reflexes—which differ from vestibular behaviors like postural control or vestibular perception (Merfeld et al. 2005a, 2005b), and are unique with regards to their neural pathways (Cullen 2012). While aging is known to be associated with changes to end-organ function (Nguyen et al. 2010; Agrawal et al. 2012; Layman et al. 2015; Li et al. 2015; Matiño-Soler et al. 2015), very little is known about whether such changes are concomitant with ARHL. One recent study conducted by Zuniga et al. (2012) investigated the relationship between ARHL and vestibular end-organ functioning and found that older adults with ARHL (especially high-frequency loss) had significantly smaller cVEMP amplitude responses than older adults with NH. In another recent study, reduced cVEMP amplitudes and greater latencies were again found to be associated with ARHL (Abdel-Salam 2020), although no other tests of vestibular end-organ functioning were conducted. It is not yet clear how these differences in end-organ functioning are related to differences in vestibular-mediated behavior or perception.

AGE-RELATED HEARING LOSS AND STANDING BALANCE

Several empirical lab-based studies have sought to better understand the mechanisms underlying poor mobility-related outcomes associated with ARHL. For instance, studies have strategically manipulated the availability of spatially relevant information during standing balance tasks by reducing (e.g., through sound suppression; Gago et al. 2015; Vitkovic et al. 2016), amplifying (e.g., through hearing aids; Vitkovic et al. 2016; Negahban et al. 2017; Kowalewski et al. 2018), or modifying (e.g., providing or removing auditory landmarks) sound cues in the testing environment (see Carpenter & Campos and Lubetzky et al. 2020 for reviews). The results of these studies, however, have been inconsistent with respect to the nature of hearing-balance interactions (see Carpenter & Campos 2020; Lubetzky et al. 2020 for reviews).

Importantly, many of these behavioral vestibular studies have not controlled for vestibular end-organ function or dysfunction, which may be present within their participant samples. Some studies have controlled for *clinically significant* vestibular impairments (e.g., Meniere's disease) based on self-report measures (see Jiam et al. 2016; Agmon et al. 2017, for reviews) without measuring subclinical *declines* in vestibular functioning. Measuring subtler declines in vestibular functioning may provide a more sensitive indicator of the role of vestibular functioning in the previously observed mobility problems reported in those with ARHL. Thus, the extent to which the observed associations between HL and falls risk are driven specifically by declines in vestibular functioning remains poorly understood. Here, we consider the possibility that better indicators of subclinical vestibular decline may be offered by measurements of vestibular *perception.*

AGE-RELATED HEARING LOSS AND VESTIBULAR PERCEPTION

At the intersection of vestibular end-organ functioning and vestibular-mediated behaviors is vestibular *perception*. While the literature describing vestibular perception in older adults is relatively limited, there is some indication that older adults demonstrate poorer vestibular perception compared with younger adults for y- and z-translations (i.e., otoliths), and roll-tilt (canal-otolith integration), but not yaw rotation (i.e., horizontal canals) (Kingma 2005; Roditi & Crane 2012; Chang et al. 2014; Bermúdez Rey et al. 2016; Karmali et al. 2017; Beylergil et al. 2019). Perception of pitch movements have not yet been tested in the older adult population. Importantly, many of the earlier-described age-related changes to vestibular perception are observed in the absence of clinically diagnosed vestibular dysfunction. They have also not been considered relative to measures of sway (e.g., centre of pressure [COP] path length) during standing-balance tasks. This is with the exception of studies that have related vestibular perceptual thresholds with failure to complete the hardest condition of a Romberg Balance Test (eyes closed, standing on a compliant surface; Bermúdez Rey et al. 2016; Karmali et al. 2016; Beylergil et al. 2019). Still, the extent to which such age-related declines in vestibular perception (e.g., *presbyvestibulopathy*; Agrawal et al. 2019) may be found in individuals with ARHL remains unknown.

CURRENT OBJECTIVES

As far as we are aware, there have been no studies comparing vestibular perceptual sensitivities in individuals with and without ARHL. Here, we hypothesized that older adults with ARHL would demonstrate higher vestibular perceptual thresholds relative to older adults with NH, even in the absence of clinically diagnosed vestibular impairments. In this study, we measured (a) otolith and canal functioning using VEMPs and vHIT, (b) behavioral balance functioning using static posturography, and (c) vestibular perception using psychophysical tasks. Specifically, we assessed vestibular perceptual passive movement detection and discrimination thresholds during heave (z axis) translation, which stimulates mainly the saccule of the vestibular system, and during pitch rotation, which involves the anterior and posterior semicircular canals as well as saccular (Fernandez & Goldberg 1976; Murofushi et al. 2013) and utricular stimulation. We expected that older adults with ARHL would demonstrate higher detection and discrimination thresholds (i.e., poorer vestibular perceptual sensitivity) than older adults with NH. These effects were predicted to be observed in (1) heave, due to the association between saccular response as measured by reduced cVEMP (i.e., saccular) amplitude and ARHL (Zuniga et al. 2012; Abdel-Salam 2020), and (2) pitch, due to the importance of pitch motion perception in mediating falls in older adults (Van den Bogert et al. 2002; Roos & Dingwell 2013, but see Bermúdez Rey et al. 2016 for the associations between failing a balance task and roll-tilt perceptual thresholds). We also performed a series of exploratory correlations between our experimental measures (vestibular psychophysical perceptual thresholds and posturography COP path lengths) and baseline assessment measures (pure-tone audiometric thresholds, self-reported measures of hearing ability, self-reported measures of balance ability, and cognitive test scores) across all participants.

MATERIALS AND METHODS

Participants

Eligibility Criteria • Community-dwelling older adults were recruited for this study and were screened over the phone and excluded if they reported having a history of stroke, seizures, diagnosed vestibular disorder (e.g., Meniere's disease), disabling musculoskeletal disorder, acute psychiatric disorder, dementia, or mild cognitive impairment, and were unable to provide informed consent. Individuals recruited for this study were confirmed to have either NH or ARHL. Specifically, participants were considered to have NH if their audiometric, pure-tone average (PTA), which was tested at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, was less than 25 dB HL. Participants were ineligible for this study if they presented with posttraumatic HL, congenital HL, middle ear problems, or asymmetrical HL (binaural difference of at least 15 dB HL at more than two adjacent frequencies). Audiometric testing was completed as per guidelines established by the International Organization for Standardization (ISO; ISO 8253-1, 1989), and classification of HL was determined by the criteria specified by the World Health Organization (1991; Stevens et al. 2013; Hume 2019; Olusanya et al. 2019) based on binaural thresholds rather than better ear (see Figures A and B in Supplemental Digital Content 1 http://links.lww.com/EANDH/A882, which shows individual participant thresholds). All but five participants were able to come to the laboratory to have their hearing assessed by pure-tone audiometry during the period of the study. Of the five who were not able to come into the laboratory to have their hearing tested, two had previously received a clinical diagnosis of ARHL and were wearing hearing aids at the time of the study; they were placed in the HL category. The remaining three participants were placed in the NH group because they had self-reported NH, and their scores (mean = 7.18) on the *Speech, Spatial, and Qualities of Hearing* (SSQ) did not differ statistically from the SSQ scores of other participants in the NH group (mean = 9.68, $p = 0.25$). Further, it was confirmed that these three participants were not group outliers in terms of their experimental task performance compared with other participants in the NH group.

Study Sample • A total of 52 participants met the eligibility criteria following a Baseline Assessment Session (described later) and proceeded to take part in the Experimental Session. Of these participants, six had to be excluded: one due to motion sickness during the experiment, two due to inability to understand and complete the task, one due to complications with the experimental setup, and two due to technical issues. The current analyses, therefore, include data from 23 participants with ARHL (mean = 73.9 years old, SD = 7.32, range = 62–87, 13 females and 10 males) and 23 participants with NH (mean = 70.2 years old, SD = 5.20, range = 65–89, 13 females and 10 males). Eleven participants from the ARHL group were hearing aid users. Participants provided informed written consent and received $10/hour for their participation. This study was approved by the Research Ethics Boards of the University Health Network, The Hospital for Sick Children, and the University of Toronto.

Baseline Assessment Session

Hearing • Pure-tone audiometry was conducted to determine audiometric hearing thresholds using a Grason-Stadler 61 Clinical Audiometer (GSI-61; Grason-Stadler Inc., Eden Prairie, MN) and Telephonics TDH-50P (Telephonics Corporation, Farmingdale, NY) headphones. Testing was administered by two authors (G.A.G. and J.J.G.) who were trained by a clinical audiologist (M.K.P-F.) and performed at a laboratory at the University of Toronto in a double-walled sound-attenuating booth (Industrial Acoustics Company, Inc., New York, NY). Octave frequencies were tested in each ear between 250 Hz and 8000 Hz. See Table 1 for a summary of all Baseline Assessment outcome measures for each group.

Otoscopy and tympanometry were used to check for abnormal middle-ear function in a subset of participants (OAHL: n = 9, 5 females, 4 males; OANH: n = 9, 5 females, 4 males) who were available to come in for testing. None of these participants were found to have excessive wax or middle ear problems.

The Speech, Spatial and Qualities of Hearing Scale (SSQ) comprises three separate scales that measure subjective abilities to hear spoken language in day-to-day settings ("Speech"), to accurately perceive the direction or location of a sound source ("Spatial"), and to perceive the clarity of a given real-world auditory stimulus ("Qualities") (Gatehouse & Noble 2004). The maximum average test score is 10 points, which is the total combined average of all tested items and would indicate that the participant reported no hearing difficulties.

Participants with hearing aids (n = 11) also completed the International Outcome Inventory for Hearing Aids (IOI-HA; Cox & Alexander 2002) to assess the perceived usefulness of their hearing devices in managing their HL. The highest possible average score is 5, which would indicate peak comfort, quality, and perceived usefulness of their device.

Cognition • Mild cognitive impairment was screened for using the Montreal Cognitive Assessment (MoCA; Nasreddine et al. 2005). The MoCA is a rapid general cognitive abilities test designed to screen individuals for mild cognitive impairment. The test assesses attention, executive function, memory, and language and is scored out of a total of 30 points. Level-of-education adjusted scores are reported. All but eight participants included in this study obtained scores of 26 or higher (indicative of normal cognition). Specifically, four participants with ARHL obtained scores of 23/30 (n = 2), 24/30 (n = 1), and 25/30 (n = 1) and four participants with NH obtained scores of 23/30 (n = 1) or 25/30 (n = 3). Vestibular perceptual thresholds and COP path length did not differ significantly between these participants and other participants.

Vestibular Function • vHIT and VEMPs were used to measure semicircular canal and otolith organ functioning, respectively. vHIT, measured by Interacoustics EyeSeeCam (Middlefart,

TABLE 1. Summary of baseline assessment measures

Baseline Measure	Hearing Loss (SD)	Normal Hearing (SD)	p
Demographics			
Participants (n)	23	23	–
Age (yrs)	73.90 (7.32)	70.20 (5.20)	0.053
Female:male (n)	13:10	13:10	
Hearing			
PTA threshold (dB HL)*	39.20 (11.60)	11.00 (5.40)	**<0.001**
Hearing aid users (n)	11	–	
IOI-HA	4.30 (0.47)	–	
SSQ total	7.42 (1.35)	9.68 (2.18)	**<0.001**
SSQ (speech)	6.23 (1.44)	8.46 (1.27)	–**<0.001**
SSQ (spatial)	7.15 (1.57)	8.63 (1.35)	**0.004**
SSQ (qualities)	7.84 (1.28)	8.95 (0.91)	**0.004**
Cognition			
MoCA (/30 total)	26.71 (2.00)	26.86 (1.78)	0.798
Vestibular end-organ			
vHIT (n)†	18	14	
vHIT (right ear)	0.94 (0.16)	0.92 (0.18)	0.749
vHIT (left ear)	0.86 (0.16)	0.87 (0.13)	–0.874
cVEMP (n)	15	19	–
cVEMP (present, right ear)	50%	89.47%	**–0.011**
cVEMP (present, left ear)	46.70%	73.68%	–0.114
oVEMP (n)	14	19	–
oVEMP (present, right ear, n)	35.71%	36.84%	0.949
oVEMP (present, left ear, n)	7.14%	36.84%	0.051
Balance			
ABC (%/100)	88.17 (13.58)	95.24 (5.17)	0.058
Participants who fell in the last year (n)	3	3	>0.999
Participants with near falls in last year (n)	6	2	0.120
Participants with fear of falling (n)	7	2	–0.063

p values represent the results of independent samples, two-tailed t-tests between the two groups, apart from the last three rows, which presents results of chi-squared tests. Bolded p-values represent significant results (p < .05).

**Binaural PTA; frequencies tested: 500, 1000, 2000, and 4000 Hz, inclusive*

†vHIT; due to the nature of the task, some participants were not able to come back to complete this session. Median gain for 60 ms reported. Only two participants (1 HL and 1 NH) obtained median gains below the 0.7 cutoff score at 60 ms, in either or both ears.

ABC, Activities-specific Balance Confidence Scale; cVEMP, cervical vestibular evoked myogenic potential; IOI-HA, international outcome inventory for hearing aids; MoCA, Montreal Cognitive Assessment; oVEMP, ocular vestibular evoked myogenic potential; PTA, pure tone average; SSQ, Spatial, Spatial and Qualities Hearing Scale; vHIT, Video Head Impulse Test.

DK), assesses the function of the lateral semicircular canals by measuring participants' vestibulo-ocular reflex (VOR). To perform this test, participants wore a pair of goggles equipped with an eye-tracking device (EyeSeeCam goggles by Interacoustics). This equipment consists of a set of lightweight goggles with built-in gyroscopes to sense head movement and a high-speed (220 Hz) camera for video-oculography. Following calibration, participants are instructed by the examiner to fixate on a stationary dot, located approximately 1.2 m away, while the examiner rotates their head using quick precise motion (head rotation 15 to 20°, duration 150 to 200 ms, peak velocity 150 to 200 deg/s, 20 impulses per side) in the planes of the semicircular canal being tested. The relative characteristics of head and eye movements are then calculated and displayed in the form of tracings, allowing for the detection of both overt and covert saccades, which heralds a side-specific abnormality in end-organ function. Perfect canal functioning evokes counter-rotational eye movements that directly mirror that of the imposed head movements, resulting in a VOR gain of 1.0. Impaired canal functioning, however, reduces eye velocity relative to head velocity, lowering the VOR gain and requiring the eyes to produce compensatory saccades to reinstate fixation following the head turn. Instantaneous horizontal VOR velocity gains were calculated by the EyeSeeCam VOG software at 60 ms. Specifically, a velocity gain was calculated by dividing instantaneous eye velocity by instantaneous head velocity. Potential vestibular dysfunction was identified if the vHIT gain was <0.7 based on prior literature (MacDougall et al. 2013; McGarvie et al. 2015; Halmagyi et al. 2017; Janky et al. 2017).

To evoke VEMP responses, short, high-intensity (97 dB nHL, 500 Hz) tone bursts were presented to the participant's ear via insert headphones. Responses were collected using the Neuroscan Synamps 2 (Compumedics Neuroscan, El Paso, TX) in most participants (HL: n = 6; NH: n = 10) and through the Interacoustics Eclipse EP25 (Interacoustics, Denmark) for the remaining participants (HL: n = 9; NH: n = 9). The tone bursts were 4 ms in duration and were presented at a rate of 5.1 Hz. Electrodes were placed on the skin above the ipsilateral sternocleidomastoid muscle in the neck, which responds to saccular stimulation (cVEMP) and on the skin above the muscles underneath the contralateral eye, which responds to utricular stimulation (oVEMP). Participants were asked to flex their sternocleidomastoid muscles for 20 seconds during cVEMP recording by lifting and tilting their heads upward and away from the side being tested. For oVEMPs, ocular muscles were contracted by having the participants look upward for 20 seconds. During the tests, myogenic responses to the auditory stimuli were recorded from the electrodes and used as a proxy for otolith functioning. At least 100 sweeps were collected in 2 trials.

cVEMPs were normalized using contraction strength measured by rectified activity in a pre-stimulus latency window, using EEGLAB. cVEMPs were scored as “present,” indicating normal otolith function if amplitude peaks were present within defined latency ranges (cVEMP P1: 10 to 25 ms, cVEMP N1: 20 to 40 ms, oVEMP N1:8 to 20 ms; oVEMP P1: 15 to 30 ms). These latency ranges were based on expected peak latencies (Li et al. 2014) and the possibility that these peaks latencies can change with age (Piker et al. 2013; Maheu et al. 2015). Absence of wave peaks within either or both of these ranges were coded as “absent” and indicated potential dysfunction of the otolith organs. Ratings of oVEMPs and cVEMPs were completed separately by a registered clinical audiologist (M.H.) and one of the authors (G.A.G.) who were blinded to participant and group. Their ratings demonstrated high inter-rater reliability (88% agreement). Disagreements in ratings were resolved by using another trained author’s blind assessment of the VEMP (J.J.G.).

Balance • Self-reported balance confidence during day-to-day tasks was measured using the Activities-specific Balance Confidence (ABC) scale (Powell & Myers 1995). Participants could receive a maximum score of 100%, indicating excellent perceived balance confidence and a minimum score of 0% indicated very poor subjective balance confidence. During the experimental session, standing balance was also measured using a posturography task (see details later).

Demographics and Health History Questionnaire • A questionnaire was administered to gather information on the participants’ demographics and medical background. Items included questions regarding education, occupation, potential noise exposure due to work environments or hobbies, ear infections, tinnitus, dizziness, history or presence of vestibular disorders, fear of falls, history of falls, smoking and drinking habits, subjective cognitive decline, heart disease, and other vascular or neurological health problems.

Experimental Session

Vestibular Psychophysics Tasks

Stimuli and Apparatus

The vestibular psychophysics tasks were performed within the KITE—Toronto Rehabilitation Institute’s Challenging Environment Assessment Laboratory (CEAL). CEAL contains a 6.0 m × 5.6 m × 4.1 m enclosed laboratory, which was mounted on a 6-degrees-of-freedom hexapod motion base with 60 in actuator arms allowing tilting up to 100 deg/s^2 in the pitch axis, and 8 m/s^2 in the heave direction (Fig. 1).

Fig. 1. Schematic of the laboratory setup for the psychophysical task.

The laboratory was outfitted with a specially constructed chair designed to minimize participants’ head and body movements. The chair was cushioned with foam to reduce vibrotactile feedback. Participants were secured using a four-point harness and rested their feet on foam mats to restrict leg movement and vibrotactile cues. A neck pillow was used to further limit proprioceptive feedback through incidental movement of the head or neck. Finally, participants were blindfolded and wore noise-canceling headphones that presented white-noise throughout each block to limit the sound created by the hydraulics of the motion base.

Movement Specifications

There were four psychophysical tasks: heave detection, heave discrimination, pitch detection, and pitch discrimination. The point of rotation for pitch movements was at the approximate center of the head. Each trial consisted of (1) a standard movement and (2) a comparison movement presented in random order. For detection, the platform remained stationary during the standard movement (see Table 2 for movement specifications). Magnitudes are stated as peak accelerations for both heave (m/s^2) and pitch (deg/s^2) motions.

Each full trial lasted approximately 20 seconds (see Fig. 2 for an example of a full heave discrimination trial). The movements all followed the same profile (Naseri & Grant 2012). The platform was oscillated at 0.5 Hz either in pitch or heave beginning at rest. The platform was then oscillated sinusoidally around this resting position with a peak velocity that increased along a raised cosine velocity envelope reaching the desired value. The platform then oscillated with this first peak velocity and the corresponding peak accelerations. The peak velocity then changed in magnitude along a raised cosine velocity envelope and then oscillated with a second peak velocity and acceleration (i.e., the second movement of the trial) before returning back to rest.

Procedures

Participants completed both a detection task and a discrimination task for each of the two motion types (pitch and heave) resulting in four psychophysical conditions. The four conditions (heave detection, heave discrimination, pitch detection, pitch discrimination) were administered in a random order across participants. In total, these four conditions took approximately one hour per participant to complete.

Detection

Each individual trial in the detection condition was composed of two intervals: (1) a motion interval (in pitch or heave, depending on the condition) and (2) a no motion interval. The order of these two intervals were randomized across trials within a condition. After both intervals were presented, participants were asked to state out loud which of the two intervals was the one in which they had moved (“one” or “two”). The acceleration of the motion was varied using a *Parametric Estimation by Sequential Testing* procedure (PEST, Taylor & Creelman 1967) until the participant’s detection threshold was reached. PEST is an adaptive staircase procedure that quickly and efficiently converges on perceptual thresholds, in this instance, corresponding to where participants were 70.7% correct (Merfeld 2011). To vary the values presented logarithmically, the base-10

TABLE 2. Initial peak accelerations used for the psychophysical tasks

Movement Type	Detection Task	Discrimination Task
Heave	Standard movement = 0 m/s^2 Initial comparison movement = 0.5 m/s^2	Standard movement = 1.0 m/s^2 Initial comparison movement = 1.5 m/s^2
Pitch	Standard movement = 0 deg/s^2 Initial comparison movement = 3 deg/s^2	Standard movement = 20 deg/s^2 Initial comparison movement = 26 deg/s^2

logarithms of the acceleration values (beginning with the initial comparison movement value; see Table 2) were used by the PEST and the log output was exponentiated into peak acceleration values before being fed to the platform's motors.

Using the logged acceleration values with an initial step size of log (0.1) for heave and log (0.2) for pitch, the PEST procedure honed in on the threshold values and was terminated after eight reversals or 60 trials, whichever came first (Taylor & Creelman 1967). Thresholds were calculated by averaging the accelerations of the last three reversals.

Discrimination

As in the detection condition, the discrimination condition used a similar PEST procedure to determine participants' movement discrimination thresholds, except with the PEST being applied to

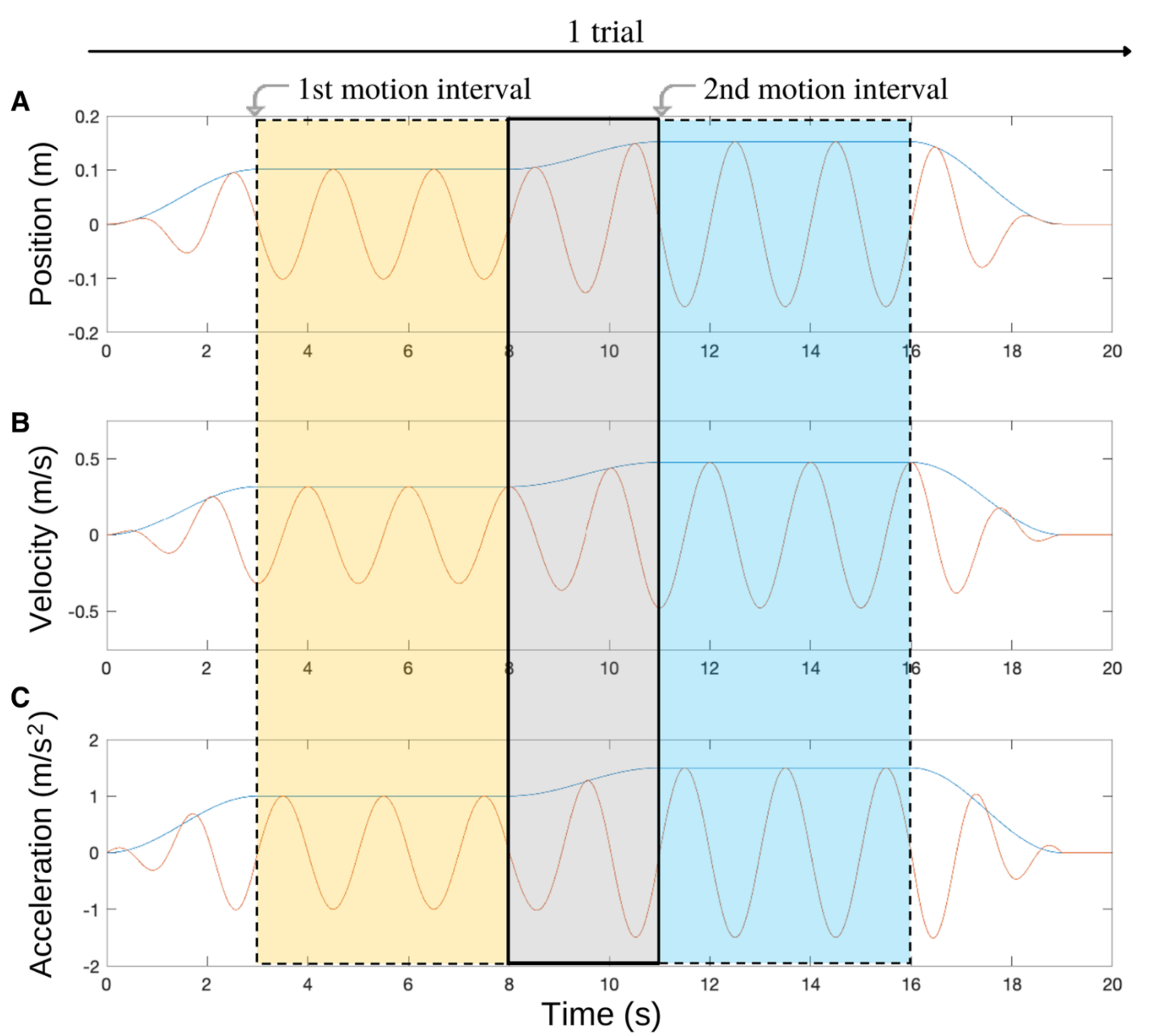

Fig. 2. Diagrammatic representation of a single heave discrimination trial. (A) the position (m) relative to the upright start position, (B) the velocity (m/s), and (C) the acceleration (m/s^2) of the motion base. For pitch trials, displacement was measured in degrees, velocity in deg/s, and acceleration in deg/s^2. The yellow area highlights the first movement (5 s; here, standard movement), the gray area represents the fade-in between the first and second movement (3 s), and the blue area represents the second movement (5 s; here, comparison movement). The white regions represent the fade from no motion to the first movement (3 s) and from the second movement to no motion (3 s), and rest (1 s).

the delta relative to the standard movement rather than the comparison amplitude. Participants were required to discriminate between two sequentially presented movements of different magnitudes in pitch or heave: one a standard movement and the other a comparison movement. Peak accelerations of the comparison movement interval were determined via the earlier-described PEST procedure using the same initial step sizes and the same termination criteria. The 70.7% correct discrimination thresholds were calculated by averaging the accelerations of the last three reversals.

Posturography Task • Participants also completed a posturography task to assess their standing balance. Participants stood in parallel pose (i.e., feet facing forward, approximately 8 in apart) for 30 seconds on a forceplate (AMTI MSA-6 MiniAmp strain gauge amplifier), which captured their center of pressure (COP) path length (cm). Signals from the forceplate were collected at a sampling rate of 1000 Hz. This was completed for four different trial types: (1) eyes open standing directly on the forceplate (EOF; "firm surface"), (2) eyes open on a piece of high-density foam placed on the forceplate (EOC; "compliant surface"; AIREX, Balance-Pad; 50 cm × 41 cm × 6 cm; density = 55 kg/m^2), (3) eyes closed on a compliant surface (ECC), (4) eyes closed on a compliant surface while wearing passive noise-canceling headphones (sound suppression; ECSS). Participants wore a loose harness during the procedure to protect against falls.

Once collected, the data were passed through a second-order zero-lag dual-pass Butterworth filter with a 6 Hz cutoff frequency. Mean COP path lengths were extracted from the data in MATLAB for each of the four trial types. COP path length was defined as the absolute length of sway in centimeters during each of the conditions. COP path length in the anterior-posterior as well as medial-lateral directions were also calculated separately.

Data Analysis

All analyses were run in R 3.6.0 (R Core Team, 2017) using the threshold values described above. All data were winsorized to treat potential outliers using the "DescTools" R package (Signorell et al. 2019). The data were then evaluated for skewness using the "e1071" package (Meyer et al. 2018), evaluated for normality using a generalized Shapiro-Wilk test for normality, and log-transformed.

Both the HL and NH participant groups were compared across various baseline measures of sensory, motor, and cognitive functioning using Welch independent sample *t*-tests (see Table 1). The groups' performances were then compared with respect to measures of vestibular detection and discrimination thresholds. A series of four independent sample *t*-tests were conducted to compare the HL group and the NH group on the thresholds obtained during each of the four psychophysical task conditions (pitch and heave detection and discrimination). We followed these analyses with a series of linear regressions, predicting the vestibular thresholds from participants' PTAs. We also used another series of multiple regressions to predict vestibular thresholds from only low-frequency, mid-frequency, or high-frequency ranges of participants' PTAs. In these regression models, we added age as an additional independent measure, alongside the PTA scores. With regards to the posturography task data, we ran a 2 (hearing group) × 4 (posturography condition) mixed-factorial ANOVA to compare the two groups' COP path lengths across the four posturography conditions (EOF, EOC, ECC, ECSS).

RESULTS

Vestibular Psychophysics Task

Discrimination Thresholds • The HL group had significantly higher pitch discrimination thresholds (mean = 5.20 deg/s^2, SD = 2.61; Fig. 3B) than did the NH group (mean = 3.50 deg/s^2, SD = 2.48; $t[41.57] = 2.40$, $p = 0.021$). There were no significant between-group differences for heave discrimination thresholds (Fig. 3A) (HL: mean = 0.32 m/s^2, SD = 0.16; NH: mean = 0.24 m/s^2, SD = 0.14; $t[43.89] = 1.52$, $p = 0.135$).

Detection Thresholds • Neither detection task revealed significant between-group differences (Fig. 3C and D). This was true for the heave detection task (HL: mean = 0.01 m/s^2, SD = 0.01; NH: mean = 0.02 m/s^2, SD = 0.03; $t[43.51] = -1.563$, $p = 0.125$), as well as for the pitch detection task (HL: mean = 0.40 deg/s^2, SD = 0.45; NH: mean = 0.33 deg/s^2, SD = 0.35; $t[43.64] = -0.062$, $p = 0.951$).

Regressing Vestibular Perceptual Thresholds on PTA Thresholds • Vestibular perceptual thresholds across both groups were regressed on their individual PTAs (Fig. 4). The results stayed largely consistent with the ANOVAs described earlier, such that larger PTAs (i.e., worse hearing) significantly predicted higher pitch discrimination thresholds but did not significantly predict pitch detection, heave detection, or heave discrimination.

Next, we calculated three new average PTA scores for each participant by averaging across the low-frequency (250 Hz and 500 Hz), mid-frequency (1000 Hz, 2000 Hz, and 3000 Hz), and high-frequency (4000 Hz and 8000 Hz) ranges, respectively. Later, we regressed each of the perceptual thresholds on these new hearing frequency groupings (low-, mid-, high frequency) and age.

Similar to the earlier-described analyses, only pitch discrimination thresholds were significantly predicted by PTA, older age, as well as their interaction (see Figs. 5B, 6B, and 7B). This was true when "PTA" referred to thresholds in the high frequency range, mid-frequency range, or low-frequency range (see Table 3). Pitch detection thresholds (Table 4) were also significantly predicted by PTA (only low-frequency), older age, and their interaction (see Fig. 7D). Analyses for all other vestibular thresholds were not significant.

Posturography

A 2 × 4 mixed-factorial ANOVA was conducted to examine the effect of group (HL and NH) and posturography condition (EOF, EOC, ECC, and ECSS) on COP path length. There was no significant effect of group ($F[1, 44] = 3.29$, $p = 0.076$), nor group × posturography condition interaction ($F[2.09, 91.95] = 0.33$, $p = 0.732$), but the test did show a significant main effect of condition ($F[2.09, 91.95] = 265.86$, $p < 0.001$; Fig. 8). Pairwise *t*-tests revealed longer COP path lengths for the harder, relative to easier, conditions, for all tasks, ($p < 0.05$) apart from ECC (mean = 73.5, SD = 36.4) relative to ECSS (mean = 77.0, SD = 38.7; $t[132] = -0.278$, $p = 0.993$).

Correlational Analyses between Experimental Measures and Baseline Measures of Sensory, Motor, and Cognitive Functioning

We also performed a series of exploratory Pearson correlations, both between and within experimental measures (vestibular thresholds, posturography COP lengths) and the baseline assessment measures (Fig. 9). These correlations were not corrected for multiple comparisons.

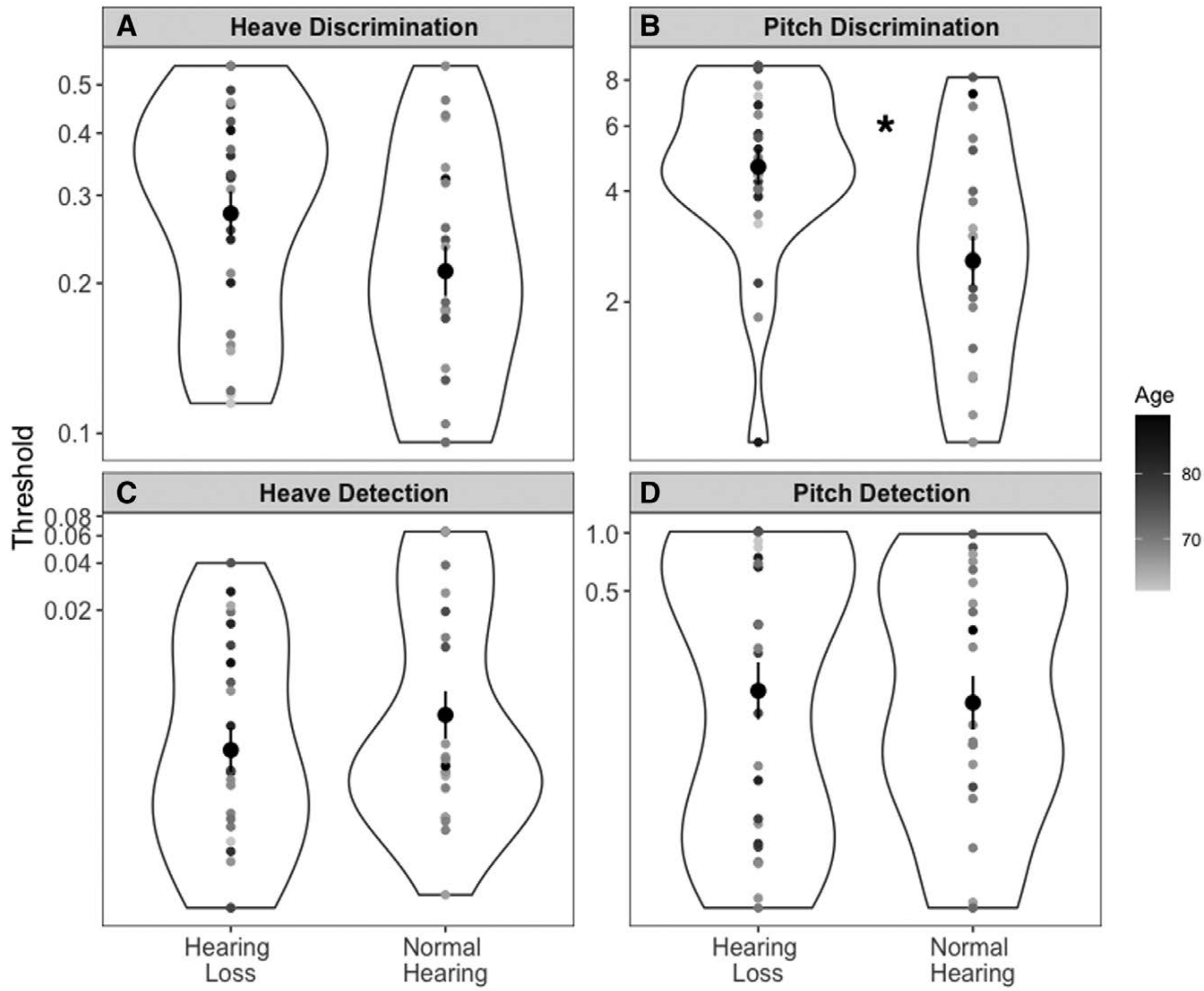

Fig. 3. Threshold values for pitch and heave detection and discrimination. Data are plotted on logarithmic scales. Thresholds for heave data are in m/s^2, and pitch data in deg/s^2. Small points represent individual data with the shade varying based on participants' age (years). The larger black points represents the group means and error bars are standard errors. Older adults with hearing loss demonstrated significantly higher pitch discrimination thresholds relative to older adults with NH. *$p=0.02$.

Vestibular Perception Thresholds Compared With Hearing Loss Measures • Pitch discrimination thresholds were negatively correlated with the *Speech* ($r=-0.38$, $p=0.020$) and *Qualities* ($r=-0.35$, $p=0.031$) scales of the SSQ, meaning that poorer pitch discrimination was associated with worse self-reported hearing. Heave detection, however, was positively correlated with the SSQ total score ($r=0.41$, $p=0.009$) meaning that poorer vestibular thresholds were associated with better self-reported hearing.

Balance Performance Compared with Hearing Loss Measures • With regards to behavioral measures of vestibular functioning, self-report measures of balance (ABC) were positively associated with self-reported hearing abilities suggesting that better self-reported balance may be associated with better self-reported hearing (SSQ; *Total*: $r=0.56$, $p < 0.001$; *Speech*: $r=0.52$, $p=0.001$; *Spatial*: $r=0.65$, $p < 0.001$; *Qualities*: $r=0.55$, $p < 0.001$). Note that age was negatively correlated with these measures (*Speech*: $r=-0.39$, $p=0.030$; *Spatial*: $r=-0.45$, $p=0.011$; *Qualities*: $r=-0.42$, $p=0.019$; ABC: $r=-0.37$, $p=0.048$). ABC scores and PTAs were negatively correlated, suggesting that higher balance confidence might be associated with lower hearing thresholds (i.e., better hearing) ($r=-0.36$, $p=0.032$). Posturography did not seem to be well correlated with PTA average or SSQ scores, except for COP-ML in the EOC condition (*Qualities:* $r=-0.35$, $p=0.029$; PTA: $r=0.41$, $p=0.008$).

Balance Compared with Vestibular Perception Thresholds • Pitch discrimination thresholds were positively correlated with COP path length on the most difficult posturography task, both for total COP path (ECSS, $r = 0.38$, $p = 0.011$) length and anterior-posterior COP path length (ECSS-AP, $r=0.33$, $p=0.025$), suggesting that lower vestibular thresholds in pitch discrimination might be associated with less postural sway. Pitch detection thresholds were positively associated with EOF for total COP ($r=0.71$, $p < 0.001$), AP-COP ($r=0.65$, $p < 0.001$), and ML-COP ($r=0.50$, $p < 0.001$).

Heave detection thresholds were also positively correlated with most of the posturography conditions, across, both, total, and AP-COP path lengths, except ECC for total COP path length (EOF: $r=0.31$, $p=0.038$; EOC: $r=0.42$, $p=0.003$; ECSS:

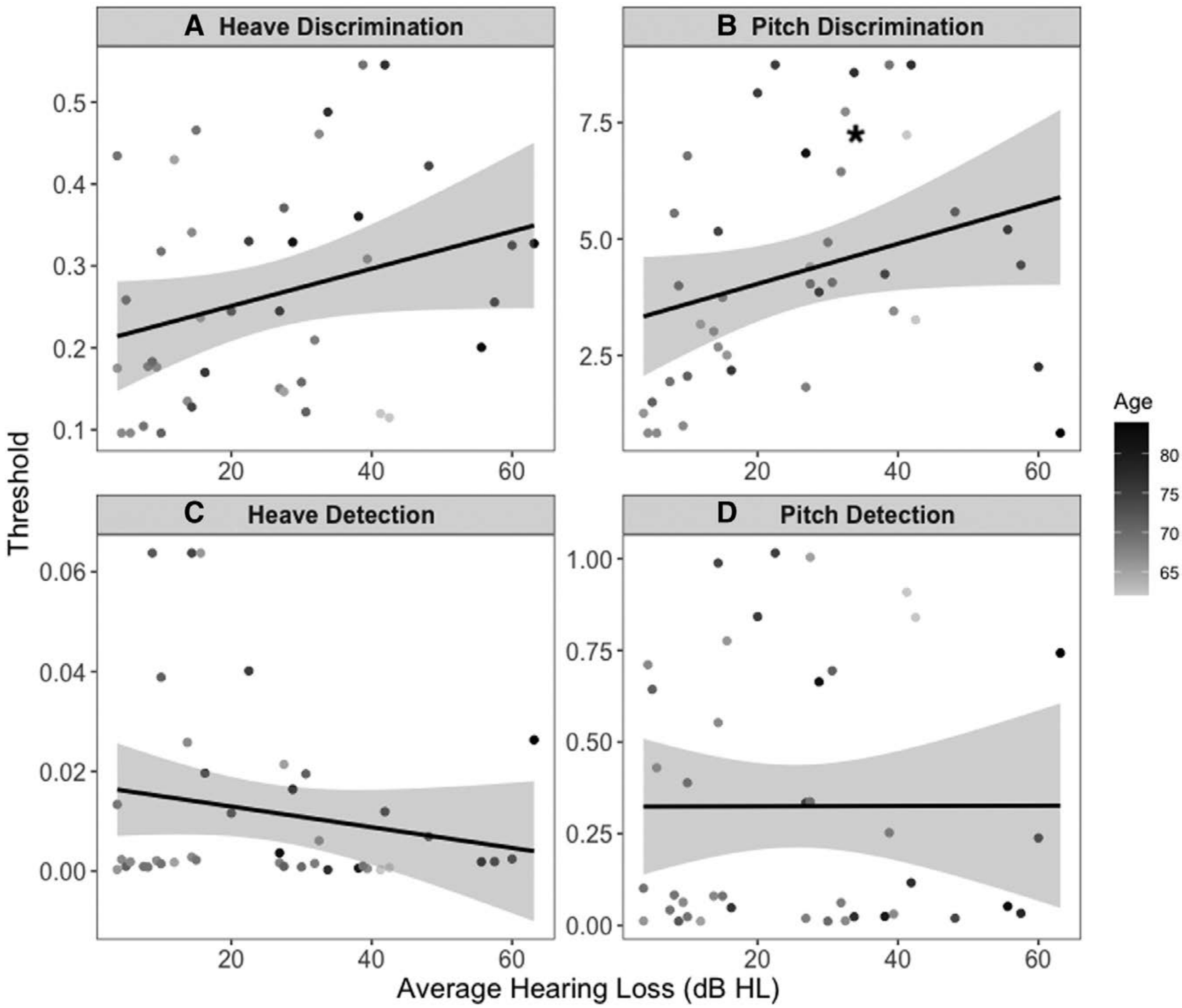

Fig. 4. Threshold values for pitch and heave detection and discrimination against PTA. Threshold values for pitch and heave detection and discrimination are plotted on the y axis, as a function of participants' binaural PTAs for frequencies 500, 1000, 2000, and 4000 Hz on the x axis. Thresholds for heave data are in m/s^2, and for pitch data in deg/s^2. Small points represent individual data with the shade varying based on participants' age (years). Older adults with hearing loss demonstrated significantly higher pitch discrimination thresholds relative to older adults with NH. * $p < 0.05$.

$r=0.32$, $p=0.029$; EOF-AP:.30, $p=0.040$; EOC-AP: $r=0.35$, $p=0.017$; ECC-AP: $r=0.30$, $p=0.042$; ECSS: $r=0.38$, $p=0.009$), suggesting that lower vestibular thresholds might be associated with less postural sway. Heave discrimination was positively associated with COP-ML in the ECC ($r=0.41$, $p=0.005$) and ECSS ($r=0.32$, $p=0.033$) conditions, and negatively associated with COP-AP in the EOC ($r=–0.33$, $p=0.025$) condition and COP-ML in the EOF ($r=–0.31$, $p=0.038$) condition.

DISCUSSION

We investigated whether older adults with ARHL show worse vestibular detection or discrimination abilities, relative to older adults with NH. We found that older adults with ARHL had significantly worse pitch discrimination thresholds relative to older adults with NH, despite no previous diagnosis of clinically significant vestibular impairments. These results were consistent when age was controlled and regardless of whether HL was treated as a categorical or continuous variable, or which frequencies were included when calculating PTAs. Furthermore, low-frequency hearing thresholds also predicted pitch detection thresholds, with low-frequency HL being associated with higher pitch detection and discrimination thresholds. No between-group differences were observed for heave discrimination, heave detection, or standing balance.

When examining the associations between behavioral balance-related outcomes and perceptual thresholds across groups, there was some evidence that higher perceptual sensitivity for some of the perceptual tasks might be associated with more stable balance—although the results of these correlations were not corrected for multiple comparisons and future research will be needed to determine the real-world implications of these findings. There were also interesting negative associations between self-reported hearing abilities and pitch discrimination thresholds across groups, indicating that poorer self-reported hearing might be associated with higher pitch thresholds (i.e., poorer pitch perceptual sensitivity).

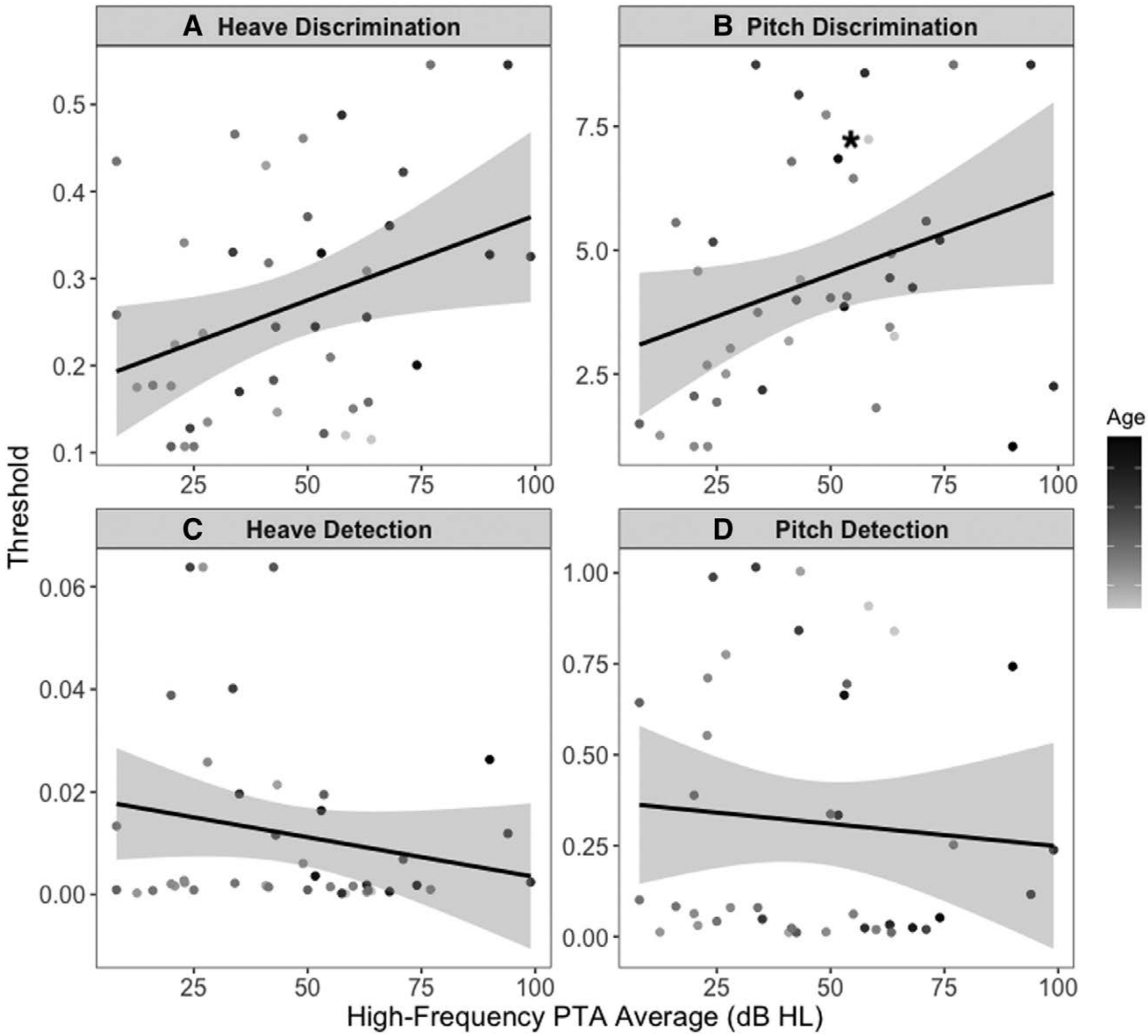

Fig. 5. Threshold values for pitch and heave detection and discrimination against high-frequency PTA. Threshold values for pitch and heave detection and discrimination are not plotted on logarithmic scales on the y axis, as a function of participants' binaural PTA average thresholds (for all octave frequencies between 4000 to 8000 Hz) on the x axis. Thresholds for heave data are in m/s², and for pitch data are in deg/s². Small points represent individual data with the shade varying based on participants' age (years). Older adults with hearing loss demonstrated significantly higher pitch discrimination thresholds relative to older adults with NH. *$p = 0.002$.

Vestibular Perceptual Thresholds in Individuals With and Without ARHL

Across vestibular perception tasks, older adults with ARHL showed higher pitch discrimination thresholds than older adults with NH. Pitch detection thresholds were also predicted by HL, but only in the low-frequency range. However, there were no observed between-group differences for heave detection or discrimination. These results provide foundational evidence for possible associations between poorer vestibular perception in those with ARHL compared with NH peers and are complementary to previous studies showing increased falls risk, and differences in vestibular end-organ functioning.

These results also provide some emerging evidence suggesting a possible association between metabolic forms of HL and increases in pitch perception thresholds, since HL in the low-frequency range specifically predicted increased perceptual thresholds in both pitch detection and discrimination (Schuknecht 1974; Schmiedt 2010; Dubno et al. 2013).

Future studies could strategically recruit participants with different audiogram phenotypes to further probe the possibility of an association between ARHL etiology and changes in vestibular perception.

Pitch Motions • The results generally point to a potentially unique role for pitch perception in differentiating vestibular differences in those with and without ARHL. Pitch perception may be particularly important for balance recovery and falls avoidance (e.g., perceiving forward or backward tilting during loss of balance; Van den Bogert et al. 2002; Roos & Dingwell 2013). Indeed, fall recovery success is known to be associated with faster reaction times during forward-tilt from balance upset to the onset of recovery response (Smeesters et

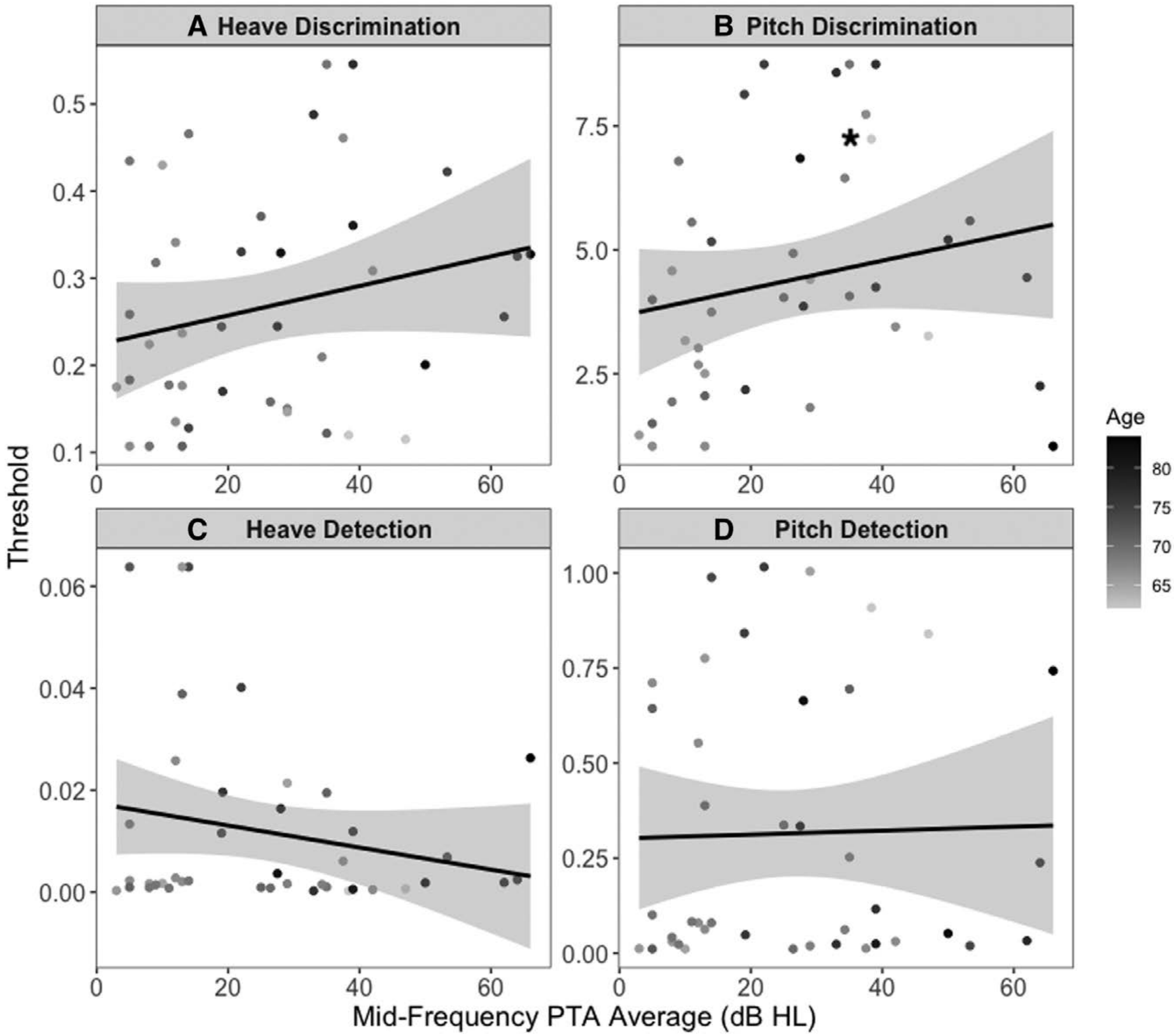

Fig. 6. Threshold values for pitch and heave detection and discrimination against mid-frequency PTA. Threshold values for pitch and heave detection and discrimination are not plotted on logarithmic scales on the y axis, as a function of participants' binaural PTA average thresholds (1000 and 2000 Hz) on the x axis. Thresholds for heave data are in m/s^2, and for pitch data are in deg/s^2. Small points represent individual data with the shade varying based on participants' age (years). Older adults with hearing loss demonstrated significantly higher pitch discrimination thresholds relative to older adults with NH. *$p < 0.002$.

al. 2001; Van den Bogert et al. 2002; de Boer et al. 2010; Roos & Dingwell 2013). Therefore, poorer pitch perception in individuals with ARHL might contribute to previously observed increased falls risk in this group. Pitch involves stimulation of the anterior and posterior semicircular canal as well as the saccule (Fernandez & Goldberg 1976; Murofushi et al. 2013) and the utricle. Saccular responses as measured by cVEMPs were more often absent in the ARHL group, relative to the NH group, in the right ear (Table 1). We did not, however, find significant differences in the left ear, nor did we observe significant differences in lateral canal or saccular function as measured by vHIT and oVEMP, respectively, between the two groups.

Heave Motions • There were no differences between the ARHL and the NH group with regards to heave detection and discrimination thresholds. This is counter to our hypothesis that ARHL would be associated with poorer heave perception—predictions that were motivated by studies reporting associations between HL in older adults and otolith functioning measured using cVEMP responses (Zuniga et al. 2012; Abdel-Salam 2020), which are sensitive to saccular end-organ function. The saccule would be most involved in signaling heave. Consistent with the lack of difference in heave responses (Fig. 3) we found no difference in saccular function as measured by cVEMP responses between the groups in the left ear, but we did find a significant difference in the right ear, with older adults with ARHL presenting with significantly fewer saccular responses as measured by cVEMP (Table 1).

Detection versus Discrimination Task • Effects of HL on perceptual thresholds were observed only for the pitch discrimination task and not the pitch detection task (except when considering low-frequency thresholds, alone - see Fig. 7d). Here, we consider a number of possibilities, which may explain this outcome. First, there are some notable differences to consider

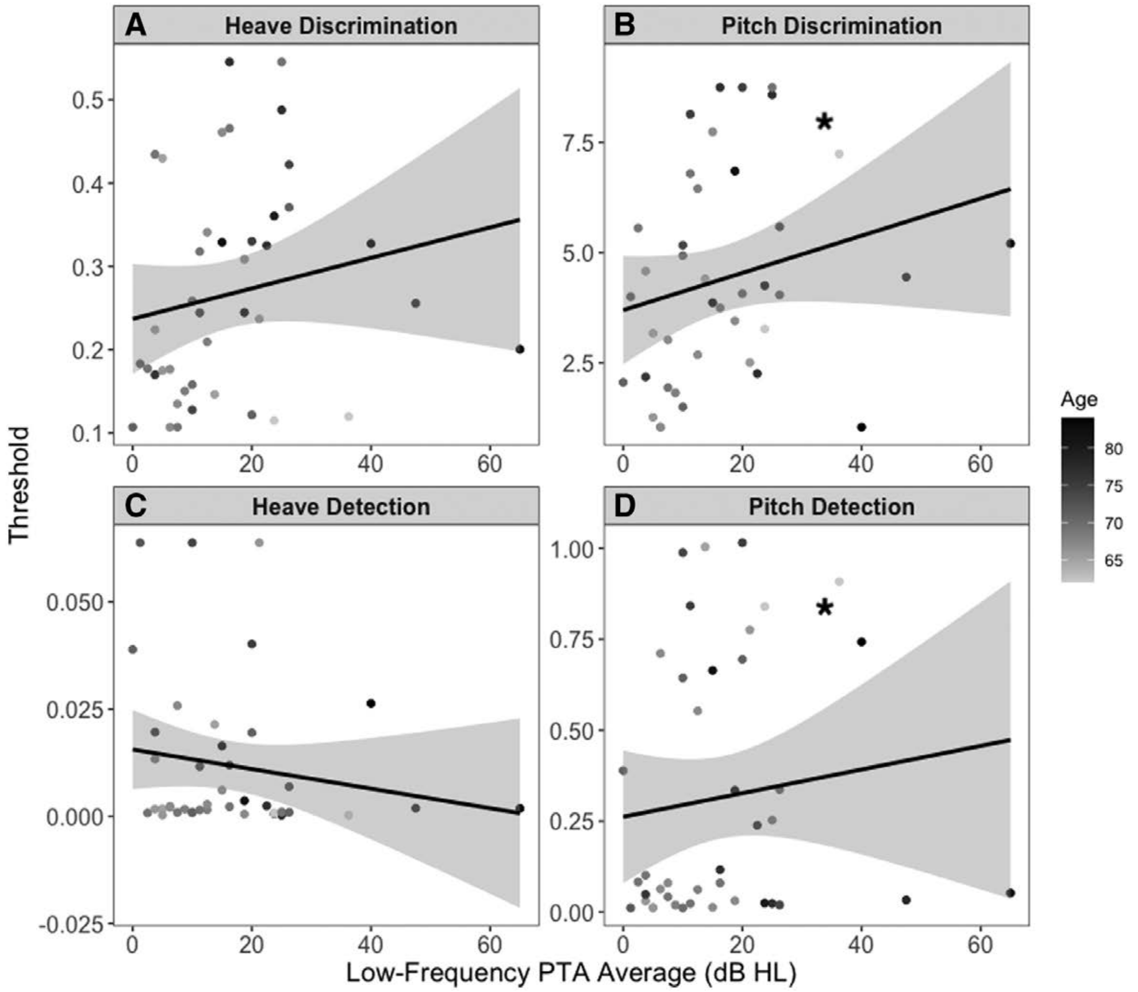

Fig. 7. Threshold values for pitch and heave detection and discrimination against low-frequency PTA. Threshold values for pitch and heave detection and discrimination are not plotted on logarithmic scales on the y axis, as a function of participants' binaural PTA (250 and 500 Hz) on the x axis. Thresholds for heave data are in m/s^2, and for pitch data are in deg/s^2. Small points represent individual data with the shade varying based on participants' age (years). Older adults with hearing loss demonstrated significantly higher pitch discrimination ($p < 0.02$) and pitch detection ($p < 0.02$) thresholds relative to older adults with NH.

TABLE 3. Results of the multiple regression analyses for pitch discrimination thresholds

Predictor	*t*	*p*	*β*	SE	*F*	df	*p*	adj. R^2
High-frequency PTA								
Overall model					5.07	3, 36	0.005	0.24
(Intercept)	–2.79	0.008	–36.76	13.17				
PTA	3.27	0.002	0.72	0.22				
Age	2.99	0.005	0.56	0.19				
PTA × Age	–3.13	0.003	–0.01	0.003				
Mid-frequency PTA								
Overall model					4.69	3, 36	0.007	0.22
(Intercept)	–2.95	0.006	–29.50	9.99				
PTA	3.50	0.001	0.90	0.26				
Age	3.30	0.002	0.47	0.14				
PTA × Age	–3.42	0.002	–0.01	0.004				
Low-frequency PTA								
Overall model					3.02	3, 36	0.040	0.14
(Intercept)	–1.91	0.064	–15.86	8.30				
PTA	2.66	0.012	0.84	0.32				
Age	2.33	0.026	0.27	0.12				
PTA × Age	–2.55	0.015	–0.01	0.004				

The dependent variable for all three models was pitch discrimination.

TABLE 4. Results of the multiple regression analyses for pitch detection thresholds

Predictor	*t*	*p*	*β*	SE	*F*	df	*p*	adj. R^2
Low-frequency PTA								
Overall model					2.14	3, 36	0.11	0.08
(Intercept)	–2.33	0.026	–5.88	2.52				
PTA	2.43	0.02	0.23	0.10				
Age	1.88	0.07	0.07	0.04				
PTA × age	–2.36	0.02	–0.003	–0.001				

The dependent variable for this model was pitch detection.

between the ability to detect versus discriminate movements, which may have facilitated performance for the detection task, relative to the discrimination task (Merfeld 2011; Chaudhuri & Merfeld 2013; Kobel et al. 2021). For example, while this study was designed to limit the availability of nonvestibular sensory cues as much as possible, the presence of subtle somatosensory cues may have still influenced perceptual judgments (e.g., support surfaces of the chair and receptors in the abdominal cavity; Mittelstaedt 1996). During the detection task, participants were required to make a binary judgment of whether they moved or not, rather than more subtle distinctions between how much they moved as was required by the discrimination task. Even slight nonvestibular cues during the "movement" compared with "no movement" intervals may have reduced reliance on purely vestibular inputs and also facilitated perceptual judgments, thereby limiting potential group effects. Future studies could consider adding additional vibrational masking noise during the no movement interval to control for this potential factor (Merfeld 2011).

Posturography

Our results, which showed no differences in COP path length between groups, are consistent with several other studies that used similar tasks and group comparisons and did not observe group-related effects (e.g., Negahban et al. 2017; Kowalewski et al. 2018). Still, the present findings are inconsistent with other studies showing less stable posture in those with HL (e.g., Gago et al. 2015; Negahban et al. 2017).

In a recent review of the effects of HL on balance, Carpenter and Campos (2020) concluded that there is a great deal of variability in the tasks and measures used across studies, possibly resulting in mixed evidence that HL affects postural stability. It is possible that our 30s posturography may not have been long enough to capture changes in COP length (Le Clair & Riach 1996; Duarte & Zatsiorsky 2000; Carpenter et al. 2001; Visser et al. 2008; Carpenter & Campos 2020) or that dynamic posturography tasks may be more sensitive in detecting differences in falls risk by considering balance recovery abilities and response to balance perturbations.

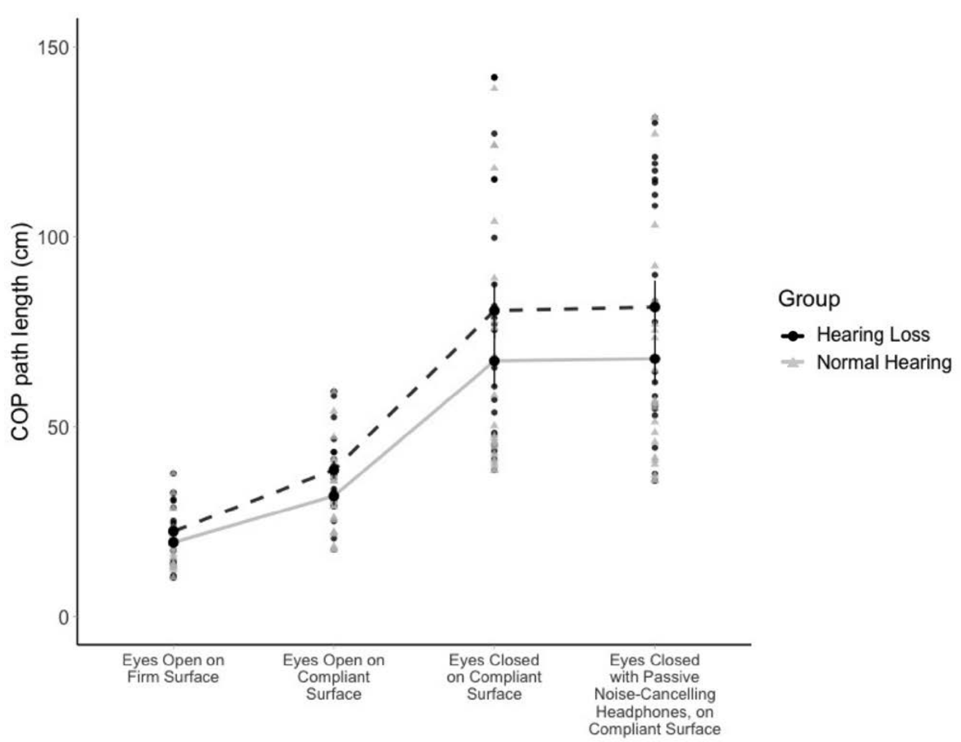

Fig. 8. Mean COP path length for each of the four posturography conditions for both groups. Individual participant data are plotted as single points. Means and standard error bars are represented by the larger black circles and error bars, respectively. While some of the data were log-transformed in the analyses, they were not log-transformed when plotted. No significant differences were found with regards to COP path length between the hearing loss group and NH group.

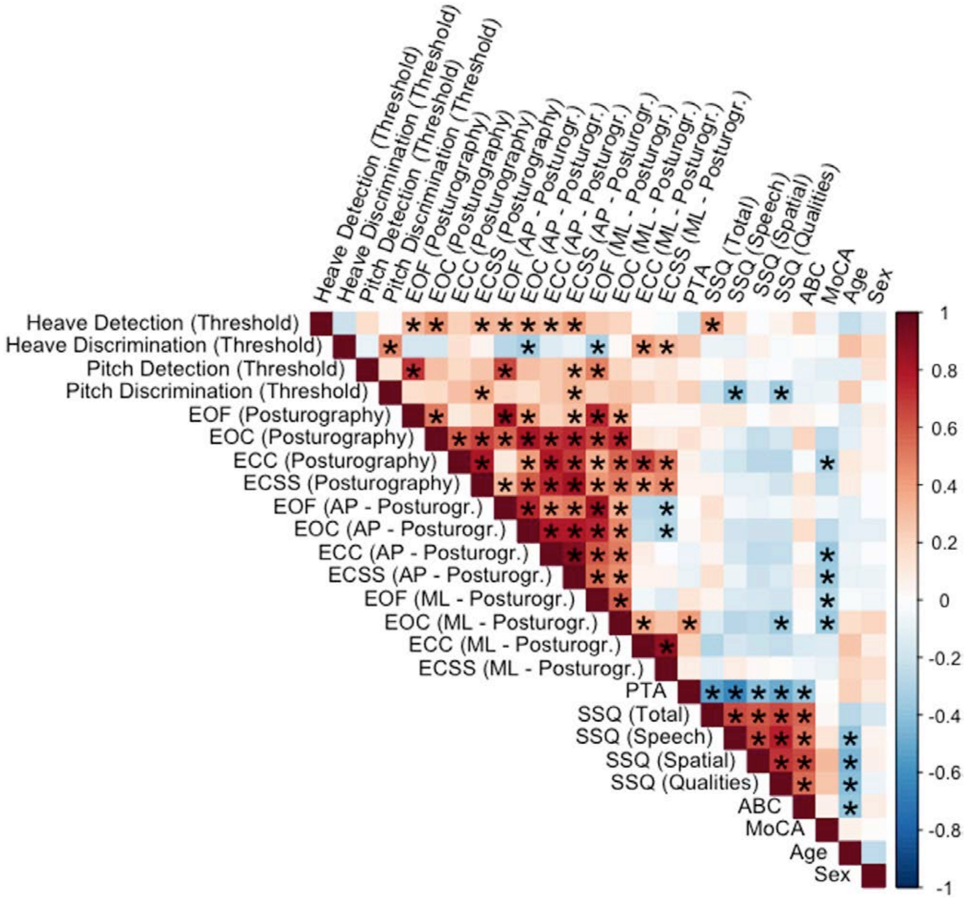

Fig. 9. Correlation heatmap demonstrating the relationship between psychophysical thresholds, COP path length, and baseline measures of hearing, mobility, and cognitive functioning. Blue squares represent negative correlations and red squares, positive correlations. EOF, Eyes Open, Firm Surface; EOC, Eyes Open, Compliant Surface; ECC, Eyes Closed, Compliant Surface; ECSS, Eyes Closed, with Sound Suppression on a Compliant Surface; AP, Anterior-Posterior; ML, Medial-Lateral; PTA (dB HL; 500, 1000, 2000, and 4000 Hz); SSQ, Speech, Spatial and Qualities Hearing Scale; ABC, Activities-specific Balance Confidence Scale; MoCA, Montreal Cognitive Assessment. $*p < 0.05$

Limitations and Future Directions

Participant Sample • As previously described, the participants included in this study's sample were a particularly healthy group of older adults who were screened using restrictive eligibility criteria such as absence of mobility problems, neurological disorders, or cognitive declines. We also intentionally excluded individuals with known, self-reported clinically diagnosed vestibular impairments. This decision was made because we were interested in group-specific *declines* in vestibular sensitivities rather than vestibular impairments resulting from other etiologies (e.g., Meniere's).

Due to these strict selection criteria, the participants included in our sample may not be totally representative of community-dwelling older adults with HL, such as those typically assessed in large population-based studies (Viljanen et al. 2009; Lin et al. 2011; Lin & Ferrucci 2012; Li et al. 2013; Chen et al. 2015; Jiam et al. 2016; Agmon et al. 2017; Campos et al. 2018). Therefore, the results observed here demonstrating poorer vestibular sensitivities in individuals with HL may, in fact, be a conservative estimate of the strength of this association compared with what might be found in a broader sample of the older adult population with varying abilities and common age-related morbidities.

Movement Parameters • In this study, we evaluated changes in vestibular perceptual sensitivity using two motion types: heave and pitch. It is possible, however, that ARHL may be associated with changes to perceptual sensitivity of other motion types including movement in yaw, roll, surge, and sway. Studies on age-related changes to vestibular perception suggest that individuals' abilities to perceive certain movement types may be preserved more than others (Roditi & Crane 2012; Bermúdez Rey et al. 2016), but it remains unclear whether percepts for certain movement types are specifically affected in those with ARHL. Furthermore, different frequency, and potentially even velocity or acceleration profiles may influence the results of this perceptual psychophysical task or observed between-group differences (e.g., Roditi & Crane 2012; Bermúdez Rey et al. 2016).

Audiometric Phenotypes • ARHL may be caused by a combination of factors with sensory, neural, and metabolic subtypes (e.g., Schuknecht 1974). It has been suggested that a limited number of ARHL subtypes (i.e., sensorineural and metabolic) might be predicted from individuals' audiogram characteristics or audiometric phenotypes (Schuknecht 1974; Schmiedt 2010; Dubno et al. 2013). If changes to vestibular and auditory perpetual thresholds are caused by similar etiologies, then it is possible that certain types of ARHL may be more strongly associated with declines in vestibular perception than others. Future studies may therefore sample individuals with different ARHL etiologies or phenotypes.

CONCLUSIONS

ARHL is associated with changes in vestibular perceptual sensitivity. These associations included the following: ARHL (i.e., PTA) was found to predict higher pitch (but not heave) discrimination thresholds; low-frequency PTA was associated with higher pitch detection and discrimination thresholds; poorer self-reported hearing was associated with poorer pitch detection and discrimination thresholds; poorer PTAs were associated with poorer balance on the most difficult posturography task. This study, therefore, provides support for the hypothesis that declines in vestibular perceptual sensitivity, particularly the perception of motions around the pitch axis, may contribute to declines in physical functioning and balance in individuals with ARHL.

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G.A.G., J.J.G., and J.L.C. conceived the study. L.R.H., J.J.G., S.L.C., K.A.G., B.C.H., M.K.P.-F., and J.L.C. helped designed the study. G.A.G. and J.J.G. collected the data. G.A.G., L.R.H., and J.L.C., analyzed and interpreted the data. G.A.G. and J.L.C. drafted the article, and all authors contributed to critically revising the article.

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REFERENCES

Abdel-Salam, G. M. S. (2020). The association between age-related sensorineural hearing loss and saccular dysfunction in the elderly. *Saudi J Otorhinolaryngol Head Neck Surgery*, *22*, 7–12.

Agmon, M., Lavie, L., Doumas, M. (2017). The association between hearing loss, postural control, and mobility in older adults: a systematic review. *J Am Acad Audiol, 28*, 575–588.

Agrawal, Y., Van de Berg, R., Wuyts, F., Walther, L., Magnusson, M., Oh, E., Sharpe, M., Strupp, M. (2019). Presbyvestibulopathy: diagnostic criteria consensus document of the classification committee of the Bárány Society. *J Vestib Res, 29*, 161–170.

Agrawal, Y., Zuniga, M. G., Davalos-Bichara, M., Schubert, M. C., Walston, J. D., Hughes, J., Carey, J. P. (2012). Decline in semicircular canal and otolith function with age. *Otol Neurotol, 33*, 832–839.

Bermúdez Rey, M. C., Clark, T. K., Wang, W., Leeder, T., Bian, Y., Merfeld, D. M. (2016). Vestibular perceptual thresholds increase above the age of 40. *Front Neurol, 7*, 162.

Beylergil, S. B., Karmali, F., Wang, W., Bermúdez Rey, M. C., Merfeld, D. M. (2019). Vestibular roll tilt thresholds partially mediate age-related effects on balance. *Prog Brain Res, 248*, 249–267.

Campos, J., Ramkhalawansingh, R., Pichora-Fuller, M. K. (2018). Hearing, self-motion perception, mobility, and aging. *Hear Res, 369*, 42–55.

Carpenter, M. G., Campos, J. L. (2020). The effects of hearing loss on balance: a critical review. *Ear Hear, 41*(Suppl 1), 107S–119S.

Carpenter, M. G., Frank, J. S., Winter, D. A., Peysar, G. W. (2001). Sampling duration effects on centre of pressure summary measures. *Gait Posture, 13*, 35–40.

Carr, S., Pichora-Fuller, M. K., Li, K. Z. H., Campos, J. L. (2020). Effects of age on listening and postural control during realistic multi-tasking conditions. *Hum Mov Sci, 73*, 102664.

Carr, S., Pichora-Fuller, M. K., Li, K. Z. H., Phillips, N., Campos, J. L. (2019). Multisensory, multi-tasking performance of older adults with and without subjective cognitive decline. *Multisens Res, 32*, 797–829.

Center for Disease Control and Prevention. (2018a). *10 Leading Causes of Injury Deaths by Age Group Highlighting Unintentional Injury Deaths, United States—2018*. U.S. Department of Health and Human Services.

Center for Disease Control and Prevention. (2018b). *Leading Causes of Nonfatal Injury Reports*. U.S. Department of Health and Human Services.

Chang, N. Y., Hiss, M. M., Sanders, M. C., Olomu, O. U., MacNeilage, P. R., Uchanski, R. M., Hullar, T. E. (2014). Vestibular perception and the vestibulo-ocular reflex in young and older adults. *Ear Hear, 35*, 565–570.

Chaudhuri, S. E, & Merfeld, D. M. (2013). Signal detection theory and vestibular perception: III. Estimating unbiased fit parameters for psychometric functions. *Exp Brain Res, 225*, 133–146.

Chen, D. S., Betz, J., Yaffe, K., Ayonayon, H. N., Kritchevsky, S., Martin, K. R., Harris, T. B., Purchase-Helzner, E., Satterfield, S., Xue, Q. L., Pratt, S., Simonsick, E. M., Lin, F. R; Health ABC study. (2015). Association of hearing impairment with declines in physical functioning and the risk of disability in older adults. *J Gerontol A Biol Sci Med Sci, 70*, 654–661.

Cox, R. M., Alexander, G. C. (2002). The International Outcome Inventory for Hearing Aids (IOI-HA): psychometric properties of the English version. *Int J Audiol, 41*, 30–35.

Cullen, K. E. (2012). The vestibular system: multimodal integration and encoding of self-motion for motor control. *Trends Neurosci, 35*, 185–196.

de Boer, T., Wisse, M., van der Helm, F. C. (2010). Mechanical analysis of the preferred strategy selection in human stumble recovery. *J Biomech Eng, 132*, 071012.

Duarte, M., Zatsiorsky, V. M. (2000). On the fractal properties of natural human standing. *Neurosci Lett, 283*, 173–176.

Dubno, J. R., Eckert, M. A., Lee, F. S., Matthews, L. J., Schmiedt, R. A. (2013). Classifying human audiometric phenotypes of age-related hearing loss from animal models. *J Assoc Res Otolaryngol, 14*, 687–701.

Fernández, C., & Goldberg, J. M. (1976). Physiology of peripheral neurons innervating otolith organs of the squirrel monkey. III. Response dynamics. *J Neurophysiol, 39*, 996–1008.

Gago, M. F., Fernandes, V., Ferreira, J., Yelshyna, D., Silva, H. D., Rodrigues, M. L., Rocha, L., Bicho, E., Sousa, N. (2015). Role of the visual and auditory systems in postural stability in alzheimer's disease. *J Alzheimers Dis, 46*, 441–449.

Gatehouse, S., & Noble, W. (2004). The Speech, Spatial and Qualities of Hearing Scale (SSQ). *Int J Audiol, 43*, 85–99.

Halmagyi, G. M., Chen, L., MacDougall, H. G., Weber, K. P., McGarvie, L. A., Curthoys, I. S. (2017). The video head tmpulse test. *Front Neurol, 8*, 258.

Humes, L. E. (2019). The World Health Organization's hearing-impairment grading system: an evaluation for unaided communication in age-related hearing loss. *Int J Audiol, 58*, 12–20.

ISO 8253-1. (1989). *Acoustics-Audiometric test methods-Part 1: Basic pure tone air and bone conduction threshold audiometry*. International Organization for Standardization.

Janky, K. L., Patterson, J. N., Shepard, N. T., Thomas, M. L. A., Honaker, J. A. (2017). Effects of device on video head impulse test (vHIT) Gain. *J Am Acad Audiol, 28*, 778–785.

Jiam, N. T., Li, C., Agrawal, Y. (2016). Hearing loss and falls: a systematic review and meta-analysis. *Laryngoscope, 126*, 2587–2596.

Karmali, F., Chaudhuri, S. E., Yi, Y., Merfeld, D. M. (2016). Determining thresholds using adaptive procedures and psychometric fits: evaluating efficiency using theory, simulations, and human experiments. *Exp Brain Res, 234*, 773–789.

Karmali, F., Bermúdez Rey, M. C., Clark, T. K., Wang, W., Merfeld, D. M. (2017). Multivariate analyses of balance test performance, vestibular thresholds, and age. *Front Neurol, 8*, 578.

Kingma, H. (2005). Thresholds for perception of direction of linear acceleration as a possible evaluation of the otolith function. *BMC Ear Nose Throat Disord, 5*, 5.

Kobel, M. J., Wagner, A. R., Merfeld, D. M., Mattingly, J. K. (2021). Vestibular thresholds: a review of advances and challenges in clinical applications. *Front Neurol, 12*, 643634.

Kowalewski, V., Patterson, R., Hartos, J., Bugnariu, N. (2018). Hearing loss contributes to balance difficulties in both younger and older adults. *J Prev Med (Wilmington), 3*, 12.

Lau, S. T., Pichora-Fuller, M. K., Li, K. Z., Singh, G., Campos, J. L. (2016). Effects of hearing loss on dual-task performance in an audiovisual virtual reality simulation of listening while walking. *J Am Acad Audiol, 27*, 567–587.

Layman, A. J., Li, C., Simonsick, E., Ferrucci, L., Carey, J. P., Agrawal, Y. (2015). Association between saccular function and gait speed: Data from the Baltimore Longitudinal study of aging. *Otology and Neurotology*, *32*, 260–266.

Le Clair, K., & Riach, C. (1996). Postural stability measures: what to measure and for how long. *Clin Biomech (Bristol, Avon), 11*, 176–178.

Li, C., Zuniga, M. G., Nguyen, K. D., Carey, J. P., Agrawal, Y. (2014). How to interpret latencies of cervical and ocular vestibular-evoked myogenic potentials: our experience in fifty-three participants. *Clin Otolaryngol, 39*, 297–301.

Li, C., Layman, A. J., Carey, J. P., Agrawal, Y. (2015). Epidemiology of vestibular evoked myogenic potentials: data from the Baltimore Longitudinal Study of Aging. *Clinical Neurophysiology*, *126*, 2207–2215.

Li, L., Simonsick, E. M., Ferrucci, L., Lin, F. R. (2013). Hearing loss and gait speed among older adults in the United States. *Gait Posture, 38*, 25–29.

Lin, F. R., & Ferrucci, L. (2012). Hearing loss and falls among older adults in the United States. *Arch Intern Med, 172*, 369–371.

Lin, F. R., Ferrucci, L., Metter, E. J., An, Y., Zonderman, A. B., Resnick, S. M. (2011). Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. *Neuropsychology, 25*, 763–770.

Lubetzky, A. V., Gospodarek, M., Arie, L., Kelly, J., Roginska, A., Cosetti, M. (2020). Auditory input and postural control in adults: a narrative review. *JAMA Otolaryngol Head Neck Surg, 146*, 480–487.

MacDougall, H. G., McGarvie, L. A., Halmagyi, G. M., Curthoys, I. S., Weber, K. P. (2013). Application of the video head impulse test to detect vertical semicircular canal dysfunction. *Otol Neurotol, 34*, 974–979.

Maheu, M., Houde, M. S., Landry, S. P., Champoux, F. (2015). The effects of aging on clinical vestibular evaluations. *Front Neurol, 6*, 205.

Matiño-Soler, E., Esteller-More, E., Martin-Sanchez, J. C., Martinez-Sanchez, J. M., Perez-Fernandez, N. (2015). Normative data on angular vestibulo-ocular responses in the yaw axis measured using the video head impulse test. *Otol Neurotol, 36*, 466–471.

McGarvie, L. A., MacDougall, H. G., Halmagyi, G. M., Burgess, A. M., Weber, K. P., Curthoys, I. S. (2015). The video head impulse test (vHIT) of semicircular canal function—age-dependent normative values of VOR gain in healthy subjects. *Front Neurol, 6*, 154.

Merfeld, D. M. (2011). Signal detection theory and vestibular thresholds: I. Basic theory and practical considerations. *Exp Brain Res, 210*, 389–405.

Merfeld, D. M., Park, S., Gianna-Poulin, C., Black, F. O., Wood, S. (2005a). Vestibular perception and action employ qualitatively different mechanisms. I. Frequency response of VOR and perceptual responses during Translation and Tilt. *J Neurophysiology*, *94*, 186–198.

Merfeld, D. M., Park, S., Gianna-Poulin, C., Black, F. O., Wood, S. (2005b). Vestibular perception and action employ qualitatively different mechanisms. II. VOR and perceptual responses during combined Tilt & Translation. *J Neurophysiology*, *94*, 199–205.

Meyer, D., Dimitriadou, E., Hornik, K., Weingessel, A., Leisch, F., Chang, C.C, Lin, C.C. (2018). e1071: Misc Functions of the Department of Statistics, probability theory group (formerly: E1071), TU Wien (R package).

Mick, P., & Pichora-Fuller, M. K. (2016). Is hearing loss associated with poorer health in older adults who might benefit from hearing screening? *Ear Hear, 37*, e194–e201.

Mittelstaedt, H. (1996). Somatic graviception. *Biological Psychology*, *42*, 53–74.

Murofushi, T., Komiyama, S., Yoshimura, E. (2013). Do patients who experience episodic tilting or translational sensations in the pitch plane have abnormal sacculo-collic reflexes? *Neurosci Lett, 553*, 95–98.

Naseri, A. R., & Grant, P. R. (2012). Human discrimination of translational accelerations. *Exp Brain Res, 218*, 455–464.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., Chertkow, H. (2005). The Montreal cognitive assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc, 53*, 695–699.

National Institute on Deafness and Other Communication Disorders. (2018). *Age-Related Hearing Loss*. https://www.nidcd.nih.gov/health/age-related-hearing-loss#:~:text=Approximately one in three people,%2C doorbells%2C and smoke alarms.

Negahban, H., Bavarsad Cheshmeh Ali, M., Nassadj, G. (2017). Effect of hearing aids on static balance function in elderly with hearing loss. *Gait Posture, 58*, 126–129.

Nguyen, K. D., Welgampola, M. S., Carey, J. P. (2010). Test-retest reliability and age-related characteristics of the ocular and cervical vestibular evoked myogenic potential tests. *Otol Neurotol, 31*, 793–802.

Nieborowska, V., Lau, S. T., Campos, J., Pichora-Fuller, M. K., Novak, A., Li, K. Z. H. (2019). Effects of age on dual-task walking while listening. *J Mot Behav, 51*, 416–427.

Olusanya, B. O., Davis, A. C., Hoffman, H. J. (2019). Hearing loss grades and the international classification of functioning, disability and health. *Bull World Health Organ, 97*, 725–728.

Piker, E. G., Jacobson, G. P., Burkard, R. F., McCaslin, D. L., Hood, L. J. (2013). Effects of age on the tuning of the cVEMP and oVEMP. *Ear Hear, 34*, e65–e73.

Powell, L. E., & Myers, A. M. (1995). The Activities-specific Balance Confidence (ABC) Scale. *J Gerontol A Biol Sci Med Sci, 50A*, M28–M34.

R Core Team. (2017). *A language and environment for statistical computing*. R Foundation for Statistical Computing; 2017.

Rauch, S. D., Velazquez-Villaseñor, L., Dimitri, P. S., Merchant, S. N. (2001). Decreasing hair cell counts in aging humans. *Ann N Y Acad Sci, 942*, 220–227.

Robins, L. M., Hill, K. D., Finch, C. F., Clemson, L., Haines, T. (2018). The association between physical activity and social isolation in community-dwelling older adults. *Aging Ment Health, 22*, 175–182.

Roditi, R. E., & Crane, B. T. (2012). Directional asymmetries and age effects in human self-motion perception. *J Assoc Res Otolaryngol, 13*, 381–401.

Roos, P. E., & Dingwell, J. B. (2013). Using dynamic walking models to identify factors that contribute to increased risk of falling in older adults. *Hum Mov Sci, 32*, 984–996.

Schmiedt, R. A. (2010). The physiology of cochlear presbycusis. In S. Gordon-Salant, R. D. Frisina, A. N. Popper, & R. R. Fay (Eds.), *The Aging Auditory System* (pp. 9–38). Springer.

Schuknecht, H. F. (1974). Pathology of the ear. In *Cambridge: Cambridge-Harvard*. Harvard University Press.

Signorell, A., Aho, K., Alfons, A., Anderegg, N., Aragon, T., Arppe, A., Baddeley, A., Barton, K., Bolker, B., Borchers, H. W., Caeiro, F. (2019). *DescTools: Tools for Descriptive Statistics*. (R package version 0.99.27.) https://andrisignorell.github.io/DescTools/.

Smeesters, C., Hayes, W. C., McMahon, T. A. (2001). The threshold trip duration for which recovery is no longer possible is associated with strength and reaction time. *J Biomech, 34*, 589–595.

Stevens, G., Flaxman, S., Brunskill, E., Mascarenhas, M., Mathers, C. D., Finucane, M; Global Burden of Disease Hearing Loss Expert Group. (2013). Global and regional hearing impairment prevalence: an analysis of 42 studies in 29 countries. *Eur J Public Health, 23*, 146–152.

Taylor, M. M., & Creelman, C. D. (1967). PEST: efficient estimates on probability functions. *J Acoustic Soci Am*, *41*, 782–787.

United Nations, D. of E. and S. A. P. D. (2015). *World Population Ageing Report, Suggested Citation: United Nations, Department of Economic and Social Affairs, Population Division (2015)*. World Population Ageing.

van den Bogert, A. J., Pavol, M. J., Grabiner, M. D. (2002). Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip. *J Biomech, 35*, 199–205.

Velázquez-Villaseñor, L., Merchant, S. N., Tsuji, K., Glynn, R. J., Wall, C III, Rauch, S. D. (2000). Temporal bone studies of the human peripheral vestibular system. Normative Scarpa's ganglion cell data. *Ann Otol Rhinol Laryngol Suppl, 181*, 14–19.

Viljanen, A., Kaprio, J., Pyykkö, I., Sorri, M., Pajala, S., Kauppinen, M., Koskenvuo, M., Rantanen, T. (2009). Hearing as a predictor of falls and postural balance in older female twins. *J Gerontol A Biol Sci Med Sci, 64*, 312–317.

Visser, J. E., Carpenter, M. G., van der Kooij, H., Bloem, B. R. (2008). The clinical utility of posturography. *Clin Neurophysiol, 119*, 2424–2436.

Vitkovic, J., Le, C., Lee, S. L., Clark, R. A. (2016). The contribution of hearing and hearing loss to balance control. *Audiol Neurootol, 21*, 195–202.

Weinstein, B. E., & Ventry, I. M. (1982). Hearing impairment and social isolation in the elderly. *J Speech Hear Res, 25*, 593–599.

World Health Organization. (1991). *Report of the Informal Working Group on Prevention of Deafness and Hearing Impairment—Programme Planning*. https://apps.who.int/iris/bitstream/handle/10665/58839/WHO_PDH_91.1.pdf.

Zuniga, M. G., Dinkes, R. E., Davalos-Bichara, M., Carey, J. P., Schubert, M. C., King, W. M., Walston, J., Agrawal, Y. (2012). Association between hearing loss and saccular dysfunction in older individuals. *Otol Neurotol, 33*, 1586–1592.