EVALUATING THE EFFECT OF HEARING STATUS ON GAIT AND BALANCE IN INDIVIDUALS WITH AND WITHOUT ACCESS TO AUDITORY CUES

by

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As members of the Audiology Doctoral Project Committee, we certify that we have read the Audiology Doctoral Project prepared by: Matthew S. Mutterperl

titled: EVALUATING THE EFFECT OF HEARING STATUS ON GAIT AND BALANCE IN INDIVIDUALS WITH AND WITHOUT ACCESS TO AUDITORY CUES

and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement for the Degree of Doctor of Audiology.

David Velenovsky (May 1, 2023 10:09 PDT)
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Final approval and acceptance of this Audiology Doctoral Project is contingent upon the candidate's submission of the final copies of the Audiology Doctoral Project to the Graduate College.

I hereby certify that I have read this Audiology Doctoral Project prepared under my direction and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement.

David Velenovsky (May 1, 2023 10:09 PDT)
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Speech, Language, and Hearing Sciences

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LAND ACKNOWLEDGEMENT

We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. Committed to diversity and inclusion, the University strives to build sustainable relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

DEDICATION

Matthew S. Mutterperl

To my family, who have provided tireless support in my efforts both in and outside of this program and have instilled a desire to help individuals with compassion and competency. This paper punctuates that desire to serve those in need from an evolving evidence-based perspective from research such as this. I am honored and grateful to continue this family tradition.

To the love of my life, Adrienne; whose unwavering love and support throughout our relationship and this entire journey through the program has made me realize my own potential and desire to achieve. That is a gift that is as priceless as it is beautiful, and I could never thank you enough for giving it to me. I love you!

STUDY RESPONSIBILITIES

This Audiology Doctoral Project document was completed by both Naudy and Matt. While both individuals collaborated jointly on conception and execution of the following study, Naudy was responsible for the Introduction and Postural Sway results section, with contributions to the Discussion section. Matt was responsible for the Methods section, Gait/Lower Limb results section, with contributions to the Discussion section as well.

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Abstract

Background: It has recently been demonstrated that the importance of the auditory system's contribution to the perception of posture and mobility increases in cases where input from other systems, such as vestibular peripheral, somatosensory, and visual, is reduced or compromised There is a growing interest in how auditory cues serve as an additional input that aids in postural stability, gait and balance, and self-motion perception. Recent evidence from other investigators reveals that auditory information may be used to improve all of these, but the process is poorly understood and requires further research. However, it would appear that preliminary information from these studies makes a strong case for clinicians to consider the importance of audition when developing treatment plans for people with hearing loss that may also be experiencing ongoing vestibular involvement. This research project aims to determine the effect of hearing status on static stability while standing and dynamic movement by measuring postural sway, gait speed, and step length using multiple wireless gait sensors.

Methods: Individuals were fitted with an array of Opal sensors and were asked to complete five randomly ordered tasks (aka "conditions"). Each condition began with a measure of postural sway as a baseline. Vision was denied in all but one condition. Postural sway was measured by having participants stand upright with their feet at shoulder width, lined up at the starting mark with hands on their hips for 30 seconds. Participants then would complete another postural sway measure that immediately preceded the dynamic gait task where participants would walk down the track and return to the start position. For each "sway into walk" condition visual cues and auditory input were manipulated.

Results: Mean values for postural sway and gait/lower limb support were compared to normative data from other studies using the same gait sensor technology. Mean values for

postural sway were compared across conditions and revealed a statistically significant difference for the hearing-impaired participants when performing the first vision denied condition as compared to the normal hearing participants. The data did not demonstrate a statistical significance across the sway trials. Our data did not show any statistically significant changes between hearing-impaired and normal hearing participants during any of the trial conditions when analyzing gait parameters. A statistically significant change for gait speed and stride length was observed between our two baseline conditions. Mean values from our data collection were consistent with previously established reference intervals.

Introduction (N. Ocasio Portalatín)

There are approximately thirty million people aged sixty and older in the United States that experience varying degrees of hearing loss and prevalence increases with age. This raises public health concerns for addressing hearing loss in older adults. Presbycusis (i.e., age-related hearing loss), a common disorder associated with aging, affects 27% of adults aged 60-69 years, 55% aged 70-79 years, and 79% aged eighty and older (Lin, Niparko, & Ferrucci, 2011). Individuals with presbycusis may experience the following symptoms: tinnitus (ringing in the ears), the perception that other’s speech seems slurred, difficulty following conversation in the presence of background noise, reduced ability to hear high pitches, women and children’s voices are more difficult to discern than men’s, and moderately loud sounds that were once easily tolerated can be uncomfortable (NIDCD, 2007).

There is an extensive body of emerging literature that shows that hearing loss is associated with decreased health outcomes across different domains. These outcomes include overall poor physical health, increased falls risk, and frailty. Cognitive health and psychosocial factors include poor self-rated health, loneliness, depression, and decreased social support (Wells, Nickels, Rush, Musich, Wu, Bhattarai, & Yeh, 2020). One challenge researchers face is comparing the results of outcomes of hearing-impaired individuals that use hearing aids versus hearing-impaired individuals that are non-hearing aid users and deriving definitive factors of association versus causation. Hearing aid use and long-term health outcomes were evaluated for 666 patients enrolled in the Epidemiology of Hearing Loss Cohort of hearing aid and non-hearing aid users. Researchers evaluated these subjects under five different domains: mental health, social engagement, cognitive factors, hearing handicap and physical health (Dawes, Cruickshanks, Fischer, Klein, Klein, & Nondahl, 2015). Out of the five domains that were assessed, they concluded that hearing aids may reduce hearing handicap and promote better physical health. Additionally, the quality of aging needs to be considered when trying to comb out these factors. Research into various socioeconomic factors has revealed that independent older adults with higher incomes, who exercise regularly, and adhere to medical treatment plans are more likely to consider hearing health an important aspect of healthy aging that includes the use of hearing aids (Wells, Nickels, Rush, Musich, Wu, Bhattarai, & Yeh, 2020).

Amplification is an effective intervention for those with hearing loss, however less than 30% of older adults with hearing loss use hearing aids (NIDCD, 2021). Lin et al., (2011) reported that it is closer to 19% of the total population with varying degrees of hearing loss that use hearing aids. The American Academy of Audiology's *Task Force on the Health-Related Quality of Life Benefits of Amplification in Adults* found that hearing aid use shows a causal relationship that can help alleviate psychological, social, and emotional harmful effects of hearing loss, which allows older individuals to enjoy a higher quality of life as compared to people who do not use amplification (Chisolm et al., 2007).

In the United States, the risk of falls for elderly adults affects greater than 1 in 4 of those aged sixty-five or older (Bergen, Stevens, & Burns, 2014). The National Council on Aging (NCOA) has found that falls totaled $50 billion in healthcare costs in 2015 alone and are projected to rise each year (NCOA, n.d.). Simultaneously, decreased vestibular function due to age-related processes leads to an increased risk for falls (Allen, Ribeiro, Arshad, & Seemungal, 2017). The Centers for Disease Control and Prevention (CDC) launched the program "Stopping Elderly Accidents, Deaths, and Injuries" (STEADI), to provide guidelines for providers from varying disciplines to routinely screen, assess, and intervene to reduce the risk of falls. The CDC has introduced the STEADI protocol based on the British and American Geriatrics Societies' clinical practice guidelines for fall prevention (Stevens & Phelan, 2013). Initiatives like these allow Audiologists to expand their use of diagnostic screening tools used by other specialty providers which facilitates a total health approach to patient care. Specific to this study, aging patients that are at risk for falls may also have a hearing loss. The evidence suggests that we should address hearing loss *and* diminished balance in older adults as part of healthy aging to help patients maintain an optimal level of physical, social, and emotional functioning.

Our vestibular system is a complex network that integrates sensory information from peripheral vestibular, somatosensory, musculo-skeletal, visceral, and visual receptors as well as motor information from the brainstem, cerebellum, and cerebral cortex. The Peripheral vestibular structures, comprising the semicircular canals and otolithic organs, code angular and linear acceleration, direction, and degree of acceleration, in three dimensions as well as providing head orientation with respect to gravity. This information provides the individual with a specific mapping of their location in physical space and a representation of self-motion perception (Zalewski, 2015). The vestibular nuclei of the central connections oversee processing of the incoming sensory information by coordinating effective ocular motor reflexes and postural control that establishes static and dynamic balance (Horak, 2008).

Rosenhall and Rubin (1975) were the first to describe the aging of the vestibular system. Their histologic dissections showed that vestibular hair cell viability experiences a gradual decline after the age of seventy, although other structures may begin to deteriorate as early as the age of fifty. Further research is consistent with these findings and have even differentiated vestibular sensory hair cell loss for type I and II cells, particularly in the cristae of the semicircular canals as compared to sensory hair loss in the macular structures of the vestibule (Zalewski, 2015). Several of these studies have consistent findings that show a decline in vestibular sensory function towards the ages of 65-80, which are consistent with self-reports of individuals who are experiencing symptoms of dizziness and imbalance.

Assessment of the vestibular system is comprised of a series of tests that evaluate both sensory and central connections. Vestibular assessments are divided into two categories: 1) tests that evaluate the vestibular ocular reflex (VOR) are videonystagmography (VNG), video head impulse testing (VHIT), rotary chair, and ocular vestibular evoked myogenic potential testing (oVEMP). 2) assessments that evaluate the vestibulospinal reflex which include computerized dynamic posturography (CDP) and cervical vestibular evoked myogenic potentials (cVEMP) (Jacobson, Shepard, Barin, Burkhard, Janky, & McCaslin, 2021). There is high variability related to marginal clinical differences that represent small changes of patient-reported outcome measures that have genuine clinical value to the patient and the measurable decline of the vestibular system using diagnostic tests as compared to the consistent subtle effects that age has on the vestibular system (Zalewski, 2015). These tests then fall somewhat short in their ability to quantify anatomical deterioration and are insensitive to the central compensatory mechanisms associated with physiologic deterioration of the aging vestibular system.

Auditory information has been investigated as a source of input that may improve balance in individuals with hearing loss though the use of amplification. Rumalla, Karim, & Hullar (2014) first noted improvements in postural stability when they compared patients who used hearing aids in unaided and aided conditions. This was accomplished by performing a 30 second tandem stance test and a 30 second Romberg foam test in the presence of broadband white noise (0 – 4000 Hz) presented at 65 dB. These tests both evaluate different aspects of postural stability; specifically, the ability of the peripheral vestibular system to perform when proprioception and visual input are reduced or not available (Agrawal, Carey, Hoffman, Sklare, & Schubert, 2011). They found that on the Romberg foam test participants in the unaided condition on average could sustain their balance on the platform for approximately 17 seconds. This significantly improved in the aided condition where the participants were able to sustain their balance for 25 seconds on average. The results in the tandem stance test showed similar results where patients in the aided condition were able to maintain the position longer than in the unaided condition. They concluded that the mechanism of improvement observed could be explained by the presence of the auditory inputs that allowed participants to spatially orient to landmarks when they had access to sound using amplification.

Stevens, Barbour, Gronski, & Hullar (2017), previously found that auditory input improved static balance for those wearing hearing aids using a sway platform. They determined that the availability of external auditory cues reduced postural sway in the dark across a group of subjects who experienced various degrees of imbalance. This was measured as the root-mean-square velocity of center of pressure of a standing subject. The maximum root-mean-square velocity of center of pressure amongst subjects decreased significantly from 7.0 cm/sec in silence to 4.7 cm/sec with the addition of the provided auditory stimulus. The addition of sound allowed subjects to reduce sway overall by 41%. This was then compared to the same participants that completed an additional trial where visual cues were available to them and there was no auditory input. Here they found that participants reduced overall postural sway by 54%. This research further suggests that improvements in balance performance may be facilitated by the amplification of auditory cues in people who have hearing loss with imbalance.

Improvements in gait and balance with hearing aids (Shayman, Earhart, & Hullar, 2017) was the first study to attempt to objectively measure how much amplification from either hearing aids or cochlear implants, contributes to improved performance during the completion of multiple gait and balance tasks. They evaluated three adult users of hearing assistive devices: a cochlear implant user exposed to cytomegalovirus (CMV), a hearing aid user diagnosed with Meniere's disease, and an additional hearing aid user with age-related hearing loss. The two measures used during this experiment were changes in gait velocity and participants' performance during the Mini-Balance Evaluations Systems Test (Mini-BEST) (Yingyongyudha, Saengsirisuwan, Panichaporn, & Boonsinsukh, 2016). Results demonstrated improvement across all conditions for all participants, although the amount of improvement varied from one participant to the next. Overall, this experiment demonstrated the value an auditory stimulus as a factor in increasing confidence when a person is navigating their environment when other cues are reduced or absent.

Research in this area has been mostly completed using equipment to measure gait and balance that requires a large footprint and is not easily transported outside of a laboratory, therefore limiting the location and type of measures used. The introduction of wearable gait sensors is an efficient, low-cost, and highly portable way of providing useful information for a variety of evaluative measures for multiple health-related disciplines. In gait analysis using wearable sensors, motion sensors are attached via Velcro® straps to different parts of the subject's body. These sensors may employ multiple forms of biomedical engineering technology like, accelerometers, force sensors, and gravitational sensors to code the recorded movement signal in a variety of forms to perform multiple measures to depict different aspects of human gait cycles (Tao, Liu, Zheng, & Feng, 2012).

Of note, due to the issues related to the ongoing COVID-19 pandemic, we were unable to recruit our original target population, older individuals with and without hearing aids. However, we were able to reformulate our study as a proof of concept to execute our methodology and obtain normative data on normal hearing participants with hearing reduced via soft foam insert-type hearing protectors and three participants with varying degrees of hearing loss who used bilateral amplification. This research project aims to determine the effect of hearing status on static stability while standing and dynamic movement while walking by measuring postural sway, gait speed, and step length using multiple wireless gait sensors. We predict that decreased auditory input whether by using ear plugs or reducing hearing acuity by removing a subject's hearing aids, will result in a measurable change in sway, step length and gait speed. The goal of this study is to contribute to the development of a balance management protocol for older patients involving amplification with the aim of improving confidence in walking and thus, quality of life.

Methods (M. Mutterperl)

Participants

All participants were recruited from The University of Arizona. Participants included 13 adults (3 males, 10 females) aged between 19 and 40 years. Three participants had self-reported bilateral sensorineural hearing loss and have worn binaural amplification for at least 10-15 years of all-day use. All other participants self-reported having no hearing difficulty and comprised the normal hearing group. Students were recruited from The University of Arizona Speech, Language, and Hearing Sciences department through fliers and emails sent via campus list-servs. Participants were not financially compensated for their time.

Materials

Each participant was fitted with 7 wearable inertial sensors (Opal, APDM Wearable Technologies Inc., Portland). The sensors were placed at the following locations and secured with elastic Velcro bands for all participants: at the forehead, sternum, lumbar spine, wrists, and the dorsum of each foot (Figure 1). The Opal sensor is a small electronic device that collects kinematic data via onboard accelerometers, magnetometers and gyrometers and transmits it wirelessly to a computer running *Mobility Lab,* which facilitates quantitative analysis according to body placement (APDM Wearable Technologies Inc., Portland).

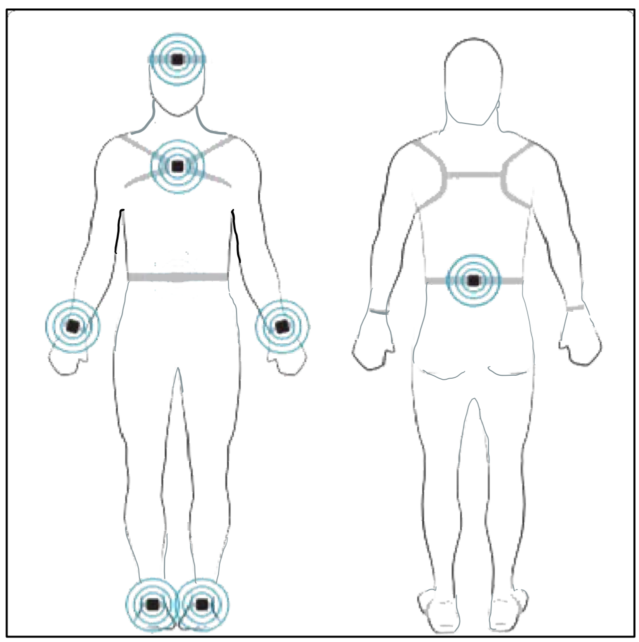

Figure 1. Opal Sensor Placement.

The variables most relevant to our study are postural sway and spatiotemporal measures of gait: speed, stride length, and double limb support. To measure these variables, participants were asked to walk down a 10m length of a hallway in the Department of Speech, Language, and Hearing Sciences, lined on one side with three speakers that would play a constant auditory stimulus during select test conditions (Figure 2). The auditory stimulus was a 10-hour YouTube video of looped crowd noise played through three Focal CMS65 6.5" powered monitors positioned on stands measuring approximately 3 feet in height. The level of this auditory stimulus was found to vary between 54-57 dBA as measured using a Brüel & Kjær precision integrating sound pressure level meter Type 2236, calibrated using a Type 4231 sound level calibrator. All 3 Focal monitors were positioned at equidistant intervals on the track such that each participant was positioned with the speaker array to their left as they began each condition. On the 10.028m track, one speaker was placed at 0.46m, the second speaker at 4.57m, and the third speaker at 9.14m. The number of speakers chosen, and their arrangement was designed to provide a consistent level of the auditory stimulus along the track for the participant to use during the walk portion of the sway-into-walk task. Markers at the beginning of the track were placed with duct tape on the hallway floor to provide proper orientation for the insteps of the feet. A duct tape marker at the opposite end of the track gave observers an endpoint to stop participants, turn them 180º, realign them at the duct tape marker, and alert participants to start walking by either vocal command or tapping their shoulder.

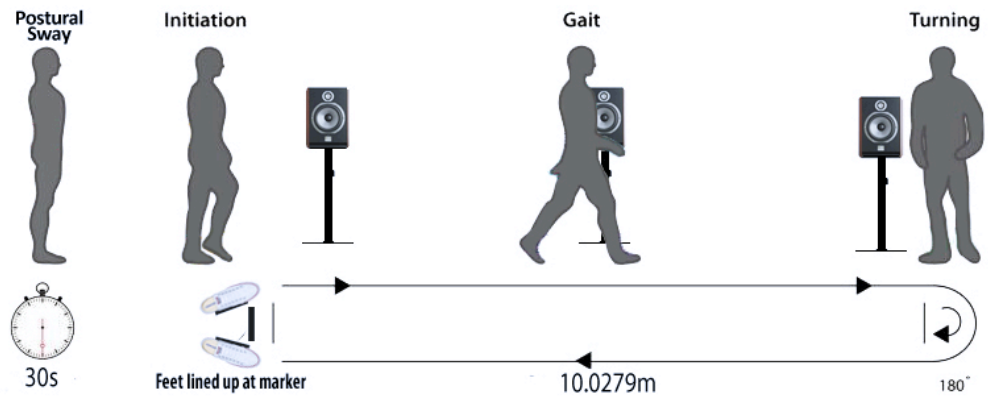

Figure 2. Schematic of dynamic gait and postural sway track with speakers.

Procedure

After completing all pre-experimental consent paperwork, individuals were fit with the array of Opal sensors. After sensors were verified to be connected to software and ready for trials, individuals completed a set of five randomized conditions. Each condition began with a measure of postural sway as a baseline prior to completing each task. Vision was denied in all but one instance. Postural sway was measured by having participants stand with their feet shoulder width apart, lined up at the starting mark with hands on their hips for 30 seconds. Participants were asked to comfortably stand as still as possible. An alert tone began each trial and played again once 30 seconds elapsed. Participants then would complete another postural sway measure for 30 seconds that immediately preceded the dynamic gait task which required walking down the hallway and back at a comfortable pace.

For each “sway into walk” condition, visual cues, hearing sensitivity, and auditory input were isolated to evaluate the contribution of the auditory system in static stability (Figure 3.).

For Condition A vision was not denied, and there was no auditory stimulus or manipulation of hearing sensitivity during the postural sway and the walk task. For Condition B, vision was denied, but an auditory stimulus was played as soon as participants began walking

A: Sway (with vision, no stimulus) | Sway (with vision, no stimulus) → Walk (with vision, no stimulus)

B: Sway (vision denied, no stimulus) | Sway (vision denied, no stimulus) → Walk (vision denied, stimulus on)

C: Sway (vision denied, no stimulus) | Sway (vision denied, stimulus on) → Walk (vision denied, stimulus on)

D: Sway (vision denied, no stimulus) | Sway (vision/hearing denied, no stimulus) → Walk (vision/hearing denied, stimulus on)

E: Sway (vision denied, no stimulus) | Sway (vision/hearing denied, stimulus on) → Walk (vision/hearing denied, stimulus on)

Figure 3. Typographic representation of all five trial conditions.

during the postural sway-into-walk task. There was no manipulation of hearing sensitivity in this condition. In Condition C, vision was denied, and the auditory stimulus played during the entire sway-into-walk task. In Condition D, vision was denied, and hearing sensitivity was manipulated for both hearing groups such that normal hearing participants completed the condition with earplugs inserted, while hearing-impaired participants completed the task after removing their hearing aids. In Condition E, vision was denied, hearing sensitivity was manipulated as previously described, and the auditory stimulus played during the entire sway-into-walk task. Conditions A and B were presented first and second respectively to all participants; however, conditions C, D, and E were randomized.

Participants were instructed to walk as normally as possible at a comfortable pace. An experimenter stood along the gait track to stabilize a subject if they appeared to be losing balance or veering towards a wall. An experimenter was present at the beginning of the track and was able to catch and redirect participants who may be veering off-track by tapping them lightly on the shoulder to indicate the direction to correct their trajectory. Another would be at the opposite end to catch the participant, stop them, turn them 180º, realign them, and then tell them to start walking. At the end of each condition, participants stood at the starting line for 5 -10 seconds prior to the start of the next trial to complete data collection.

Results

APDM software data collected was exported to an Excel spreadsheet and organized for analysis. A total of eight data subsets were selected for analysis that were processed using a general linear mixed model with pairwise comparisons (Table 1).

APDM Measure	Description
Postural Sway	
Sway Area	The area of an ellipse covering 95% of the sway angle in the coronal and sagittal planes.
Mean Velocity	Mean velocity of the sway path in the transverse plane.
Jerk	Smoothness of sway from the time derivative of the sway path in the transverse plane.
Path Length	Total length of the sway path in the transverse plane.
Root Mean Square (RMS) Sway	The RMS of the sway angle in both the coronal and sagittal planes
Gait/Lower Limb	
Gait Speed	The forward speed of the subject, measured as the forward distance travelled during the gait cycle divided by the gait cycle duration.
Stride Length	The forward distance travelled by the foot during a gait cycle.
Double Support	**The percentage of gait cycles in which both feet are on the ground.**

Table 1. Experimental Measures extracted from APDM® software.

Postural Sway (N. Ocasio Portalatín)

The APDM instrumented postural sway data collection during the Sway-Stand-and-Walk trial conditions (A-E) included the sway area (m^2/s^4), mean velocity (m/s), smoothness of trunk sway, also called jerk (m^2/s^5), path length (m^2/s^2), and root mean square (m/s^2). The sensors tracked sway movements for individual participants for 30 seconds prior to starting the ambulating portion of the task (Figure 4). It was determined that as a proof of protocol the best way to measure the validity of the trial conditions used would be to analyze data that looked

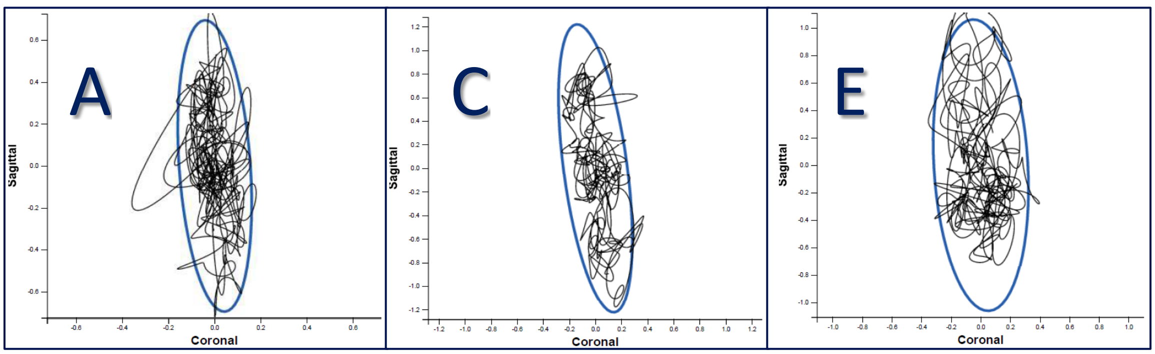

Figure 4. Sway Path Ellipsis for Conditions A, C, & E.

specifically at the sway area and mean velocities as compared to published reference intervals matched to age group that were tested during the data collection phase. The intended age group for this research project, older adults with age-related hearing loss, was not assessed due to ongoing issues associated to the Covid-19 Pandemic. The mean age of participants in the study was 25.7 years (n=13).

Voss et al., 2021, established a normative database for typically developing children and young adults aged 5-30 (Table 2). In this study they assessed a variety of sway measures using normal stance (feet shoulder width apart) with eyes open (EO) and eyes closed (EC) on a firm surface and on a compliant foam surface. The EO condition on a firm surface most closely resembles Condition A of our test protocol. The EC condition on a firm surface is similar to the

Conditions C (hearing/hearing aid available) and E (ear plugged with a hearing protective device/no hearing aid) of the developed test protocol. The one main difference between comparing the data from these two studies is that for all the conditions in our test sequence there was an available auditory stimulus collocated at approximately 45 degrees to the left of the participant at the beginning of the track prior to starting the conditions.

22-30 years	Sway Area	Mean Velocity	Jerk	Path Length	Root Mean Square
EO Firm	0.01 ± 0.01	0.08 ± 0.04	0.68 ± 0.42	5.11 ± 1.58	0.04 ± 0.01
EC Firm	0.01 ± 0.01	0.10 ± 0.03	0.85 ± 0.40	5.44 ± 1.38	0.06 ± 0.01

Table 2. Normative Postural Sway Scores by Age Group (Adapted from Voss et al., 2021)

Figures 5 and 6 show the sway area and mean velocity data sample mean and standard deviation values for the Voss et al., 2021 compared to the data collected in this study where participants sway was measured standing on a firm surfaces wth eyes opened.

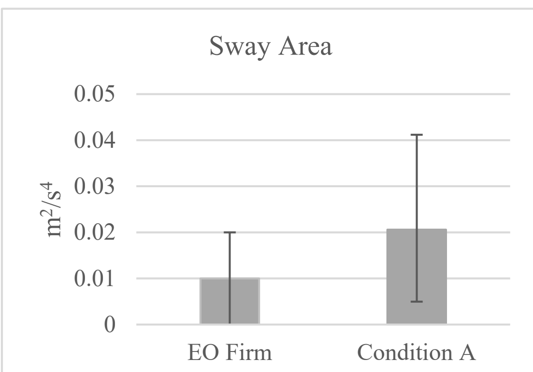

Figure 5. Comparison of mean values for Sway Area for "EO Firm" from Voss et al., 2021, "Condition A" from present study.

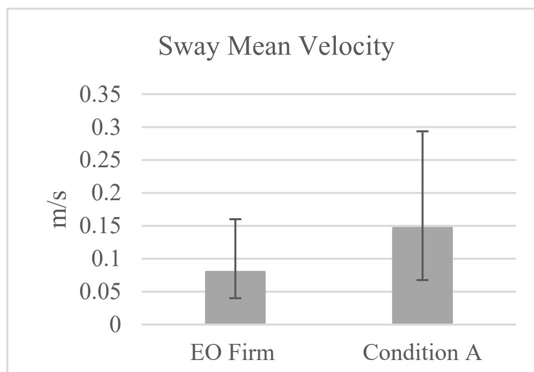

Figure 6. Comparison of mean values for Sway Mean Velocity for "EO Firm" from Voss et al., 2021, "Condition A" from present study.

The mean values for both sway variables for Condition A are larger as compared to the EO Firm task. We might expect to see changes in these values as we colllect data on more subjects and in different age groups. The means from both data sets were very similar revealing that there was not a clinically significant difference between the Voss et al. study and our data. One main variable that differs from these studies was a possible trial effect represented by the added auditory stimulus for the conditions in our protocol. Figures 7 and 8 depict the sway area and mean velocity data sample mean and standard deviation values for the Voss et al., 2021 compared to the data collected in this study where participants sway was measured standing on a firm surfaces wth eyes closed. The same mean differences were observed in these conditions when comparing Conditions C and E of the current protocol that had the additional auditory input as as compared to the previous study's reference intervals where the participants had their eyes closed on a firm surface.

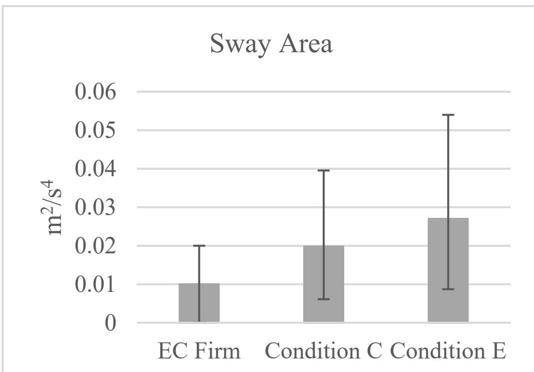

Figure 6. Comparison of mean values for Sway Area for "EC Firm" from Voss et al., 2021, "Conditions C & E" from present study.

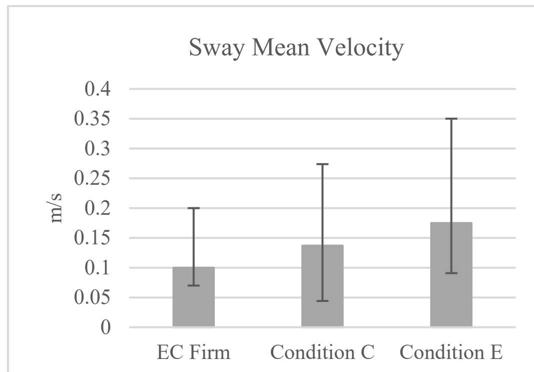

Figure 8. Comparison of mean values for Sway Mean Velocity for "EC Firm" from Voss et al., 2021, "Conditions C & E" from present study.

Another interesting trend that was observed in the data set collected for this study was the comparison for trials based on hearing status of our participants. As previously mentioned, we had three participants that had hearing loss and were experienced hearing aid users. All the hearing-impaired participants that were exposed to the B condition immediately following condition A had a statistically significant larger mean value for postural sway as compared to the normal hearing group (Figure 9). This large mean value was also noted when compared across conditions.

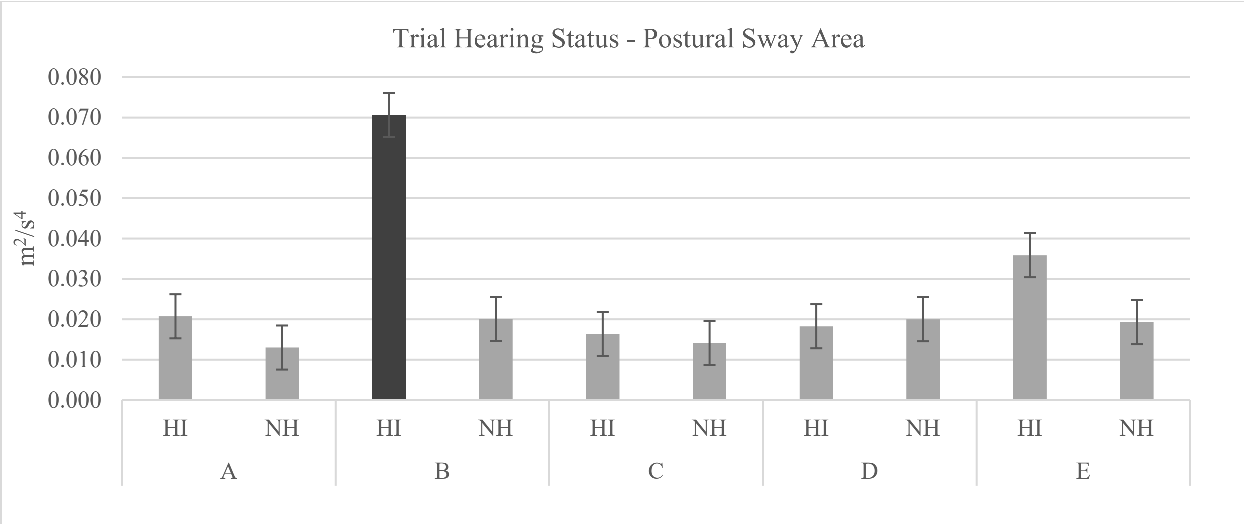

Figure 9. Mean values for trial by hearing status for postural sway area for normal hearing (NH) participants and hearing-impaired (HI).

Gait/Lower Limb (M. Mutterperl)

The APDM *Mobility Lab* data collection for dynamic gait parameters during all sway-into-walk trial conditions revealed three variables of interest to our study: gait speed (m/s), stride length (m), and double limb support (%GCT). We observed that for both hearing-impaired and non-hearing-impaired participants, a statistically significant change in gait speed and stride length occurred between the trial conditions A and B, where a blindfold was introduced in the latter condition and remained there for the last three trials. Gait speed and stride length appear to decrease in the B condition compared to the A condition, however this may be due to the fact that the B condition is the first-time participants are asked to stand or walk without vision. We did not see a statistically significant change in gait speed or stride length in conditions C, D, and E when comparing both groups.

Figure 10 illustrates the effect of trial condition on hearing status of participants in our study, revealing a similar trend between conditions where vision is available (A) and denied (B) when compared to Iosa et al. (2012). Comparing mean gait speed from condition B (vision denied with hearing) to condition D (vision and hearing denied) appears to indicate that having both vision and hearing unavailable during perambulation will increase gait speed. This could also be explained by an order effect, as condition B always preceded conditions C-E and may allow participants a chance to adapt to the lack of visual input.

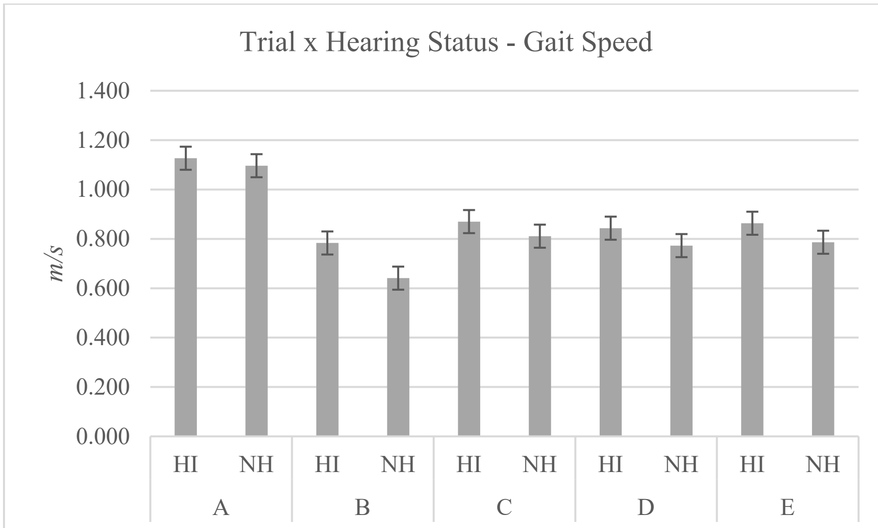

Figure 10. Effect of trial by hearing status, with mean values of gait displayed for participants with our 11 normal hearing (NH) and our three hearing-impaired participants (HI)

Mean values for stride length illustrated in Figure 11 reveal identical trends between our two baseline conditions: with vision (A) and vision denied (B). A decrease in stride length was observed when participants were blindfolded, however stride length seems to increase for conditions C-E. Looking at conditions C-E, no appreciable change between all three conditions across normal hearing- and hearing-impaired participants can be observed. Additionally, stride length seems to paradoxically increase for both groups when hearing and vision are both denied in conditions D and E compared to conditions B and C when only vision is denied.

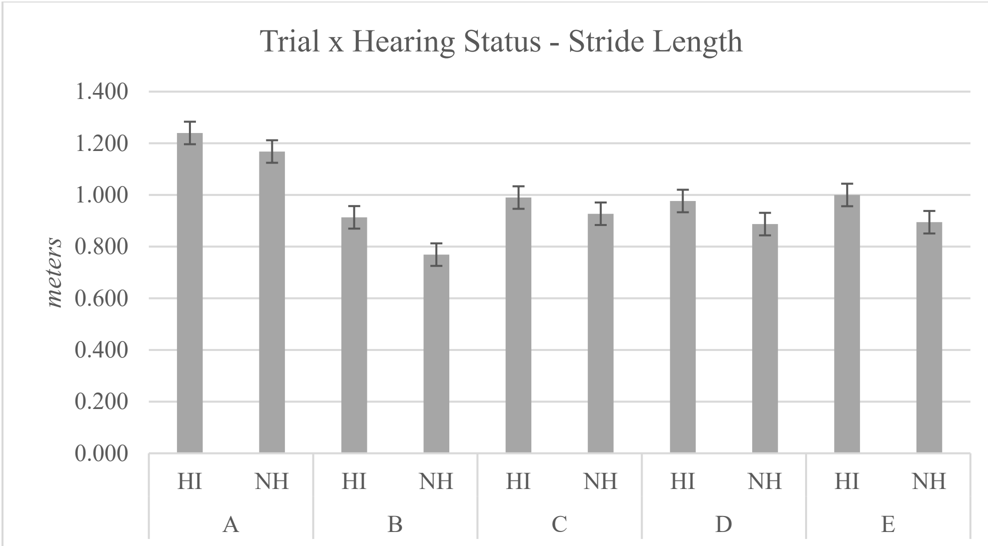

Figure 11. Effect of trial by hearing status, with mean values of stride length displayed for participants with our 11 normal hearing (NH) and three hearing-impaired participants (HI).

Double support indicates time spent with both feet on the ground during a gait cycle and is expressed as the percentage of time both feet are on the ground relative to when either foot is raised. A higher percentage can indicate unsteadiness as shorter, quicker steps may be taken when participants are unable to see. The mean values for all participants are shown in Figure 12, indicating that lack of vision resulted in more time with both feet on the ground to provide more security and stability while walking. Typically, both feet are on the ground for 20% of a gait cycle: 10% at the beginning and 10% at the end (Webster & Darter, 2001). In Figure 12, we see this for Condition A, along with an increase in percentage of time both feet are on the ground in Condition B where participants were denied vision. Although there does appear to be a slight reduction in double limb support when hearing is denied in condition D compared to condition B, this was not statistically significant for hearing-impaired or normal hearing participants.

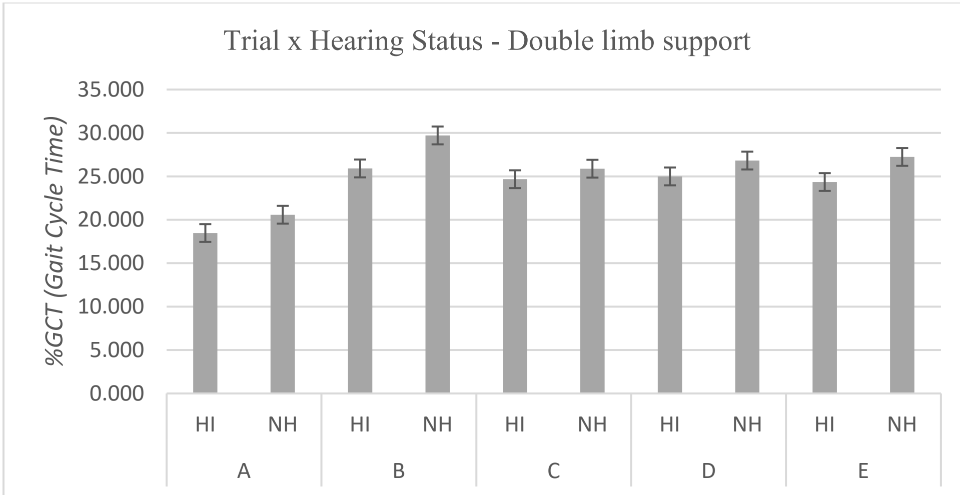

Figure 12. Mean values for double limb support in percentage of time with both feet planted during gait cycle for normal hearing (NH) and hearing-impaired (HI) participants.

Previous research can provide a cross check for results obtained in this study by comparing similar experimental paradigms and data collection methods. Iosa et al. (2012) used an inertial sensor (FreeSense, Sensorize s.r.l., Rome) to capture spatiotemporal gait parameters for a task that involved walking a 10m track with and without a blindfold. Results obtained in their study from a similarly aged group of participants reveal a marked trend when participants are asked to walk with vision denied, namely a decrease in gait speed (Iosa et al., 2012). In the table below calculated mean and standard deviation values for walking speed, which was calculated as number of steps taken over time spent walking are shown (Figure 3). Although hearing sensitivity was not manipulated during their task and only one inertial sensor was used, the authors concede that although auditory input alone cannot compensate for lack of visual input, there may be some contribution being made from the auditory system as we walk.

Condition	Walking Speed
Full Vision	1.12 ± 0.11
No Vision	0.83 ± 0.18

Table 3. Effects of Visual Deprivation on Gait Dynamic Stability (adapted from Iosa et al. 2012).

Comparing both hearing-impaired (HI) and normal hearing participants (NH) participants in our baseline condition completed with vision (Condition A) and Iosa and colleagues' participants in their Full Vision condition, differences in mean values are seen in the graph below (Figs. 13). Gait speed appears to increase when normal hearing individuals can walk with all sensory cues available (Full Vision, Condition A), but decreases when major sensory input is taken away from the system.

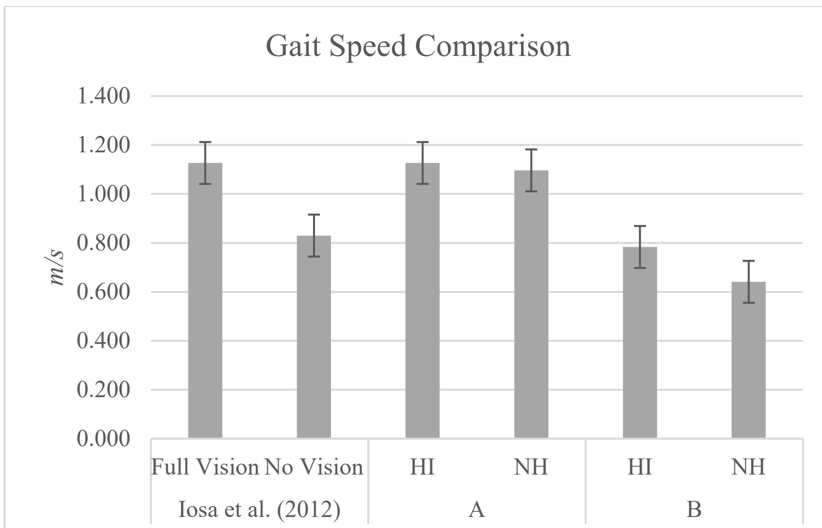

Figure 13. Comparisons in mean values for gait speed comparing Iosa et al. (2012) and the two baseline conditions (A and B) among three hearing-impaired (HI) and 11 normal hearing (NH) participants.

Discussion

There is a growing body of literature that demonstrates how auditory information influences gait and balance and makes contributions in what is thought to be perceptual mapping of one's own environment, particularly when there are limited visual and proprioceptive cues. The more we learn about these auditory contributions, the better informed we will be in determining alternatives for treatment approaches for patients experiencing vertiginous symptoms or balance insecurity who have hearing loss and can benefit from leveraging these auditory cues.

This project evolved from a study intended to recruit participants over the age of 65 diagnosed with presbycusis to a demonstration of a proof of concept. To increase generalizability, it was important to reach across disciplines and compare our data to similarly gathered data used in physical therapy research. Through examining physical therapy research, we became aware of how wearable sensors perform and how they can be incorporated into research that involves auditory stimuli with the goal of improving a patient's balance and gait stability. Overall, our data did not display statistical significance across any of the variables that we evaluated. However, a comparison of our results to previous studies demonstrates that the data from this study was on par with mean values for age-matched groups in the Voss et al. and Iosa et al. studies.

We observed certain patterns of behavior and tendencies from participants during the trials. One notable qualitative observation was that participants became more confident walking the path using a blindfold as they performed a new trial when hearing was available to them. Participants also were more cautious or slowed down their gait speed in the conditions where vision was denied and there was a decrease in auditory input. A visual analysis of the sway patterns of the participants across trials was variable in the amount of sway, but there was a general pattern of ellipses. The pattern followed a front to back sway or slightly tilted towards the left to wear the first speaker was located at approximately forty-five degrees from the participant.

There were multiple limitations to the development of this study. Ongoing health concerns associated with COVID-19 prevented us from testing our target population, older individuals with age-related hearing loss. A conscious decision was made to not recruit participants for the intended age group of patients 65 and over to avoid unnecessary exposure during an ongoing pandemic. The pandemic also negatively affected the amount of time we were able to spend collecting data. Again, regarding target population, it is possible that there may be differences in the parameters we evaluated in this experiment if we were able to compare performance between younger and older adults with hearing loss, or with two groups of older adults with and without hearing loss. In terms of study design, all participants performed conditions A & B in order and then randomized the three remaining trials potentially creating an order effect. An alternative would have been to perform an additional familiarization trial with the blindfold to acclimatize the participant to visual sensory deprivation. Another opportunity would be introducing a trial condition where the participants have vision available, and hearing is denied either by inserting the hearing protective device or removing the hearing aid.

Another question can be raised regarding the way hearing was manipulated in this study. Without having audiometric data available on all participants—especially the participants with hearing loss—it would be reasonable to assume that participants performing trials D and E without hearing aids may actually have an advantage over normal hearing participants in those conditions due to the degree and severity of their hearing loss. We also do not know exact attenuation values for each participant, so it is difficult to say unequivocally that both groups, and even individuals within groups, had similar degrees of attenuation in the hearing denied condition. One future consideration is to obtain personal attenuation ratings for each participant using a standardized protocol with a RealEar verification platform or a commercially available system. Conversely, real-ear measurements using probe tubes could verify that participants' hearing aids are fit to prescriptive gain targets. Future directions for this study would involve an audio-vestibular evaluation by way of pure-tone and speech audiometry, Video Head Impulse

Testing (hit), cervical Vestibular-Evoked Myogenic Potentials (cVEMP), and bithermal caloric irrigations.

Other future considerations for testing with this protocol include having speakers on both sides of the track for a more balanced sound environment. We believe that this may decrease some of the veering observed as a result of participants anchoring to the auditory stimulus on one side of the track. Also, the trials can be executed using auditory stimulus at different levels to see if there are any differences in performance, similar to the PI-PB-Max seen during word recognition testing used during audiologic evaluations. Increasing the subject pool for the intended population of older adults with presbycusis would also be desirable. In the past three years hearing aid manufacturers have started to include motion sensors in their devices. Incorporating these devices into our protocol could provide a unique opportunity to extract data when performing functional tasks that evaluate sway, gait, and balance with the contribution of auditory cues.

Appendix A:

Dizziness Handicap Inventory

Subject #: ____________________

Instructions: The purpose of this scale is to identify difficulties that you may be experiencing because of your dizziness or unsteadiness. Please answer "**yes**," "**no**," or "**sometimes**" to each question. *Answer each question as it pertains to your dizziness or unsteadiness problem only*.

		Y, N, S	Score
P1.*	Does looking up increase your problem?		
E2.	Because of your problem do you feel frustrated?		
F3.	Because of your problem do you restrict your travel for business or recreation?		
P4.	Does walking down the aisle of a supermarket increase your problem?		
F5.	Because of your problem do you have difficulty getting into or out of bed?		
F6.	Does your problem significantly restrict your participation in social activities such as going out to dinner, movies, dancing, or parties?		
F7.	Because of your problem do you have difficulty reading?		
P8.	Does performing more ambitious activities like sports, dancing, and household chores such as sweeping or putting dishes away increase your problem?		
E9.	Because of your problem are you afraid to leave your home without having someone accompany you?		
E10.	Because of your problem have you been embarrassed in front of others?		
P11.	Do quick movements of your head increase your problem?		
F12.	Because of your problem do you avoid heights?		
P13.	Does turning over in bed increase your problem?		
F14.	Because of your problem is it difficult for you to do strenuous housework or yard work?		
E15.	Because of your problem are you afraid people may think you are intoxicated?		
F16.	Because of your problem is it difficult for you to go for a walk by yourself?		
P17.	Does walking down a sidewalk increase your problem?		
E18.	Because of your problem is it difficult for you to concentrate?		
F19.	Because of your problem is it difficult for you to walk around your house in the dark?		
E20.	Because of your problem are you afraid to stay home alone?		
E21.	Because of your problem do you feel handicapped?		
E22.	Has your problem placed stress on your relationships with members of your family or friends?		
E23.	Because of your problem are you depressed?		
F24.	Does your problem interfere with your job or household responsibilities?		
P25.	Does bending over increase your problem?		

A "yes" response is scored 4 points. A "sometimes" response is scored 2 points. A "no" response is scored 0 points.
* "F" represents an item contained on the functional subscale, "E" represents an item contained on the emotional subscale, and "P" represents an item contained on the physical subscale.

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