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Research Article

Association Between Vestibular and Cognitive Function in U.S. Adults: Data From the National Health and Nutrition Examination Survey

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Abstract

Background. Vestibular function declines with age, and emerging evidence suggests that vestibular loss is associated with cognitive impairment. Whether vestibular dysfunction is associated with age-related cognitive decline is unknown.
Methods. We used data from the 1999–2002 National Health and Nutrition Examination Surveys to evaluate the influence of vestibular function on cognitive performance in a nationally representative sample of U.S. adults aged ≥60 years (n = 1,303). Vestibular function was measured with the modified Romberg test, and cognitive function was measured by the digit symbol substitution (DSS) score test. We also developed structural equation models (SEMs) to explore whether vestibular dysfunction and associated cognitive impairment mediate the effect of age on falls and activities of daily living (ADL) difficulty.
Results. Vestibular dysfunction was present in 58% of the study population. In multivariate analyses, vestibular dysfunction was associated with a 3.4-point lower DSS score (95% confidence interval: −5.2, −1.6; $p < .0001$), equivalent to the effect of 5 years of age. Vestibular dysfunction was also associated with a significantly higher odds of ADL difficulty ($p = .001$), and with a 2.6-fold increase in the odds of falling ($p = .017$). SEMs suggested that vestibular function mediates 14.3% of the effect of age on cognitive performance. Further SEMs suggested that lower cognitive performance mediates the association between vestibular loss and ADL difficulty as well as falls.
Conclusions. This study suggests that vestibular dysfunction partially mediates the association between age and cognitive impairment. Moreover, the cognitive impairment that results from vestibular loss may contribute to ADL difficulty and falls in older individuals.

Key Words: Balance—Cognition—Cognitive Aging—Functional Performance—Falls.

Numerous lines of evidence—including epidemiological, physiological, and histopathological—have shown that vestibular function declines with age (1,2). The vestibular system is classically known for its role in maintaining balance and postural control, and indeed several studies have noted associations between vestibular loss and balance impairment as well as falls in older individuals (3,4). Additionally, increasing evidence demonstrates important contributions of the vestibular system to various domains of cognitive function, including perceptual/visuospatial ability, memory, attention, and executive function. Studies in animals and in patients with unilateral or bilateral vestibular loss suggest that the vestibular system provides critical information about spatial orientation that subserves the higher order cognitive processes of spatial memory and spatial navigation (5,6). Clinicians have long noted anecdotally a connection between vestibular dysfunction and cognitive impairment, and have reported that complaints of memory loss and "brain fog" are commonplace among patients with dizziness and vertigo (7).

Visuospatial ability is known to deteriorate with age. Studies have shown that older individuals have greater difficulty with navigation in both real-world and virtual environments. Older subjects make more errors in returning to their starting locations, and have greater difficulty in remembering the locations of previously observed targets (8). Additionally, the perception of the subjective visual vertical also appears to degrade with age, with greater deviations from true vertical observed among healthy older compared to younger subjects (9). It is currently unknown whether vestibular loss associated with age plays a role in the degradation of these critical spatial cognitive functions in older adults. This link may be important to establish given that the association between age-related vestibular loss and falls may be mediated by declines in spatial orientation and navigation.

In this study, we use data from the National Health and Nutrition Examination Survey (NHANES) to evaluate the association between vestibular function and cognitive function. NHANES is a large-scale, highly powered survey that conducted balance and cognitive function testing on more than 3,000 individuals between 1999 and 2002. We evaluate the association between vestibular function and cognitive function in this large nationally representative data set. We develop a series of structural equation models (SEMs) to determine the extent to which the association between age and lower cognitive performance is mediated by vestibular loss. Further, we use structural equation modelling to explore hypotheses about whether lower cognitive performance cognitive may mediate the associations between vestibular function and falls and function impairment, as measured by activities of daily living (ADL) difficulty. This study offers critical insight into whether age-related loss of peripheral vestibular sensitivity contributes to the widespread and elusive condition of cognitive impairment in older adults. Moreover, these analyses explore the implications of vestibular and cognitive impairment on geriatric outcomes of substantial public health significance, including falls and disability.

Methods

Study Population

NHANES is an ongoing cross-sectional survey of the civilian, noninstitutionalized population of the United States. Every 2 years, the NHANES survey approached households and the individuals within them at random, and persons were selected to participate if they met a specific demographic profile (based on gender, race/ethnicity, age, and place of residence) and contributed to the national representativeness of the sample. Twelve to thirteen thousand individuals were selected in each of the last several cycles; the participation rate has ranged from 79% to 84%. Further details of the NHANES sampling process are available (10).

The 1999–2000 and 2001–2002 NHANES performed balance testing on a subset of a nationally representative sample of adults aged 40 years and older (one-half of adults 40–69 years of age in the 1999–2000 and all adults 40–85 years of age in the 2001–2002 study collection periods), respectively; and cognitive testing on a nationally representative sample of adults aged 60 years and older. We combined these two 2-year cycles of data to analyze 4 years of data per National Center for Health Statistics (NCHS) recommendations (10). A total of 21,004 people of all ages took part in NHANES from 1999–2002; 5,655 participants were aged 40 years and older (and between 40 and 69 years for the 1999–2000 study period). Participants were excluded from the balance testing protocol if they were unable to stand on their own, were having dizziness sufficient to cause unsteadiness, weighed more than 275 pounds, had a waist circumference that could not accommodate proper fitting of the standard-sized safety gait belt, needed a leg brace in order to stand unassisted, or had a foot or leg amputation. Participants were excluded from cognitive testing if they were less than 60 years of age or if they were unable to complete the exercise without assistance of a proxy respondent. Of the eligible adults, 1,460 participants (25.8%) were excluded because they did not participate in the NHANES physical examination for various reasons including "safety exclusion" and "participant refusal," resulting in a sample size of 4,195 participants. Of these, 925 participants did not complete the entire physical examination. Of the remaining 3,270 participants, cognitive function data was collected on 1,303 individuals aged 60 years and older. There were no significant differences between included and excluded participants with respect to gender. However, included participants were more likely to be younger and white. Sample weights for the combined 4-year sample were used per NCHS guidelines (10).

Balance Testing

Balance testing consisted of the modified Romberg Test of Standing Balance on Firm and Compliant Support Surfaces. This test examined the participant's ability to stand unassisted under four test conditions that were designed to specifically test the sensory inputs that contribute to balance—the vestibular system, vision, and proprioception. Test condition 4 was designed to test vestibular function exclusively: subjects had to maintain balance on a foam-padded surface (to obscure proprioceptive input) with their eyes closed (to eliminate visual input).

Balance testing was scored on a pass/fail basis. Test failure was defined as (a) a subject needing to open the eyes, (b) the subject moved the arms or feet in order to achieve stability, or (c) the subject began to fall or required operator intervention to maintain balance within a 30-second interval. Because each successive test condition from 1 to 4 was progressively more difficult than the condition preceding it, the balance testing component was ended whenever a subject failed to pass a test condition (either during the initial test or in the re-test if the participant opted for one). We focused on test condition 4, designed to distinguish participants who could not stay standing when relying primarily on vestibular input. We categorized participants as having vestibular dysfunction if they did not pass test condition 4. Of the sample size of 4,195 participants, 257 did not pass prior test conditions and thus did not participate in test condition 4. An additional 86 participants had missing data for test condition 4, leading to a total of 343 excluded participants (6.7%). Further details of balance testing procedures are available at http://www.cdc.gov/nchs/data/nhanes/ba.pdf.

Cognitive Function Testing

Cognitive function testing consisted of the digit symbol substitution (DSS) subtest of the Wechsler Adult Intelligence Scale, Third Edition (WAIS III). In this test, participants were given a key that paired symbols and numbers. They were then given a series of numbers, and had to draw the corresponding symbol using the provided key. Participants were given items for initial practice, and then the test was administered over 120 seconds. The DSS score was computed as the number of correct symbols, with a maximum score of 133. There were a total of 3,706 participants 60 years of age or greater who qualified for cognitive testing. Participants who were unable to complete any of the sample items were excluded from testing, leading to a total of 731 excluded participants (19.7%). Of the remaining 2,975 respondents, only 1,303 also underwent vestibular function testing described earlier.

Demographic and Health-Related Variables

Trained interviewers administered detailed questionnaires (11). Race-ethnicity was grouped as non-Hispanic white (hereafter, "white"), non-Hispanic black (hereafter, "black"), Mexican American or other. Education was grouped as less than high school, high school diploma (including GED), and beyond high school. Two participants had missing education data. Participants were asked about a history of falls ("during the past year, have you had difficulty with falling?"). Participants were also queried about their ability to perform basic and instrumental ADLs. Participants' ability to carry out 19 specific basic and instrumental ADL's (including dressing, eating, transferring, reaching, managing money, participating in social activities) were scored as 1 = "No difficulty," 2 = "Some difficulty," 3 = "Much difficulty," and 4 = "Unable to do." A composite ADL score was computed by adding all the individual ADL scores together, with higher numbers indicating greater levels of ADL difficulty and subtracting 19 to rescale the index to have a value of zero when no impairments are present (for a maximum score of 57 = 19 items × 4 points − 19). Seventy-eight (6.0%) of 1,303 participants had missing ADL data.

A complete smoking history included the number of years smoked and the current number of cigarettes smoked per day. Pack-years of smoking were computed, and participants were divided into smoking categories including never smoked, <20 pack-years of smoking, and ≥20 pack-years of smoking. There were substantial missing data ($N = 56$) on the quantity of tobacco smoked, so a separate category was made for "ever smokers with unknown pack-years" (no individuals ended up with missing data). Hypertension was defined based on physician diagnosis, use of antihypertensive medication, an average systolic blood pressure >140 mmHg or an average diastolic blood pressure >90 mmHg at the time of examination. Mean blood pressure was comprised of up to four readings on two separate occasions (one individual had missing data). Diabetes was defined based on physician diagnosis, use of antihyperglycemic medication, an 8-hour fasting glucose ≥126 mg/dL, or a nonfasting glucose ≥200 mg/dL (35 individuals had missing data). Stroke was defined based on physician diagnosis (four participants had missing data).

Audiometric and Visual Acuity Measures

Details of NHANES audiometric testing procedures have been published previously (12) and are available at http://www.cdc.gov/nchs/data/nhanes/au.pdf. Pure-tone average hearing thresholds at the frequencies 0.5, 1, 2, and 4 kHz were computed in the better-hearing ear. Details of NHANES visual acuity testing procedures have been published previously and are available at http://www.cdc.gov/nchs/data/nhanes/nhanes_01_02/vision_year_3.pdf. Nonrefracted visual acuity was coded as 20/20 (20), 20/30 (30), 20/40 (40), 20/50 (50), 20/60 (60), 20/70 (70), 20/80 (80), 20/200 (200), 20/200+ (666) in the better-seeing eye (14 individuals had missing data).

Analysis

We used multiple linear regression models to estimate the association between vestibular dysfunction and DSS score, adjusting for demographic and health-related variables. We used adjusted Poisson regression analyses to model the association between vestibular dysfunction and ADL difficulty, given the approximately Poisson distribution of the ADL impairment variable. We also evaluated the association between vestibular dysfunction and history of falls in multiple logistic regression analyses. Complete case analysis was used in multiple regression models on a sample of 1,250 individuals (53 individuals excluded due to missing covariate data). Further, we constructed a series of SEMs to explore whether vestibular dysfunction mediated the association between age and lower cognitive function, and whether the association between vestibular dysfunction and falls and ADL difficulty may be mediated by cognitive function. SEMs are multivariate regression models that are meant to represent causal relationships among the variables in the model. Unlike the more traditional multivariate linear models, the response variable in one regression equation in an SEM may appear as a predictor in another equation. The path analysis is a special case of the SEM in which there are no latent factors in the model; as such the models we are using are indeed path analyses as well as SEMs.

All analyses were adjusted for the survey design using the SVY procedures in Stata software (StataCorp, College Station, TX). Sample weights were incorporated into all analyses by using the pweight statement in Stata software per NCHS instructions. All coefficients, odds ratios, and variance estimates are presented from weighted analyses unless otherwise specified. p Values of less than .05 were considered statistically significant.

Results

The mean (standard deviation [*SD*]) DSS score of the study sample was 45.5 (17.9), range 0–100 (Table 1). DSS scores decreased significantly with age (Table 1). There were significant differences in mean DSS score by race/ethnicity, educational attainment, vestibular loss, visual acuity, and physical function. Individuals with greater than a high school education had a markedly higher DSS score compared to individuals with less than a high school education. Additionally, significantly higher DSS scores were achieved among individuals without vestibular loss, normal visual acuity, and unimpaired physical function (Table 1).

The association between vestibular dysfunction and DSS score was evaluated in multivariable analyses (Table 2). The presence of vestibular dysfunction was associated with a reduction in DSS score by −3.4 (95% confidence interval [CI] −5.2, −1.6; $p < .0001$). When expressed as multiples of the age coefficient, vestibular dysfunction had the equivalent effect on cognitive function as 4.9 years of age. Additional factors significantly associated with poorer DSS scores were male gender; black, Mexican American or other race/ethnicity (relative to whites); lower educational levels; a history of hypertension, diabetes, and poorer visual acuity (Table 2). Hearing was only measured in a subset of the analytical sample ($N = 244$), thus a separate model was run that additionally adjusted for hearing. In this model, vestibular dysfunction was associated with a reduction in DSS score by −5.0 (95% CI −9.0, −1.2; $p = .014$, data not shown).

We also evaluated the association between vestibular dysfunction and ADL composite score in multivariable analyses (Table 2). We observed that vestibular dysfunction was significantly associated with a 0.4 point increase in the aggregate ADL difficulty index (95% CI 0.2, 0.6; $p < .001$). Other factors also significantly associated with an increase in ADL difficulty were age, female gender, history of smoking, history of hypertension, and history of stroke. Participants who were Mexican American and who had increased educational

Table 1. Population Characteristics, National Health and Nutrition Examination Survey 1999–2002*

Characteristic	*N* = 1,303		
	Overall Population Characteristic	Mean DSS Score (*SD*)	*p* Value
Demographic variables			
Age, mean years (*SD*)	69.3 (7.3)	45.5 (17.9)	NA[†]
Gender, *n* (%)			.2086
Female	669 (51.3)	47.4 (18.1)	
Male	634 (48.7)	43.5 (17.6)	
Race/ethnicity, *n* (%)			<.0001
White	793 (60.9)	50.1 (16.2)	
Black	210 (16.2)	36.7 (17.4)	
Mexican American	236 (18.1)	38.3 (18.3)	
Other race	64 (4.9)	43.9 (19.5)	
Education, *n* (%)			<.0001
<High school	434 (33.6)	34.0 (16.0)	
High school graduate	331 (25.4)	47.7 (16.4)	
>High school	536 (41.2)	53.5 (15.2)	
Health-related variables			
Smoking, number of pack years (%)			.7648
Never	609 (46.7)	45.0 (18.4)	
<20	253 (19.4)	47.3 (17.6)	
≥20	385 (29.6)	45.7 (17.5)	
Unknown	56 (4.3)	41.4 (16.5)	
Hypertension, *n* (%)			.1302
Yes	857 (65.8)	43.9 (17.6)	
No	445 (34.1)	48.5 (18.2)	
Diabetes, *n* (%)			.4676
Yes	366 (28.8)	41.4 (17.8)	
No	905 (71.2)	47.1 (17.6)	
Stroke, *n* (%)			.1014
Yes	63 (4.9)	33.9 (15.8)	
No	1,236 (95.2)	46.1 (17.8)	
Vestibular dysfunction, *n* (%)			.0009
Yes	757 (58.1)	43.0 (16.6)	
No	546 (41.9)	49.0 (19.1)	
PTA average, better ear, dB (*SD*)[‡]			.3017
≤25 dB	189 (77.1)	50.7 (18.3)	
>25 dB	56 (22.9)	45.6 (18.5)	
Visual Acuity, /20 (*SD*)[§]			.0002
≤20/20	589 (45.7)	49.2 (17.7)	
>20/20	700 (54.3)	42.6 (17.4)	
Outcome variables			
History of falls[‖], *n* (%)			.7513
Yes	47 (3.6)	40.7 (17.6)	
No	1,255 (96.4)	45.7 (17.9)	
Physical function[¶], mean (*SD*)			.0430
No impairment	537 (43.8)	47.5 (18.5)	
Mild (1–4)	400 (32.7)	47.3 (16.3)	
Moderate (5–20)	259 (21.4)	42.5 (17.9)	
Severe (>20)	29 (2.4)	35.8 (18.8)	

Notes: DSS = digit symbol substitution.

*Using NHANES 1999–2002 with population-adjusted weights.

[†] No comparison was made for this population characteristic as it applies to the whole sample size.

[‡] Hearing loss defined as pure tone threshold average across 500, 1,000, 2,000, and 4,000 Hz (whichever is lower between right and left ear). Only 245 individuals from the NHANES cohort with cognitive function results reported hearing loss data.

[§] Nonrefracted visual acuity defined as: 20/20 (20), 20/30 (30), 20/40 (40), 20/50 (50), and 20/60 (60), 20/70 (70), 20/80 (80), 20/200 (200), 20/200+ (666) (whichever is lower between right and left eye).

[‖] At least one episode of falling over past 12 months.

[¶] Index aggregated and scaled by summing performance on 19 activities of daily living. Responses to individual activities range from 1 (no impairment) to 4 (complete impairment). Data was rescaled by subtracting 19 from each observation to allow the index to have a minimum value of zero, ranging from 0 (no impairment) to 57 (complete impairment).

Table 2. Multivariable Regression Model of the Association of Vestibular Dysfunction with DSS Scores of the Wechsler Adult Intelligence Scale, National Health and Nutritional Examination Survey 1999–2002*

Variable	DSS Score[†] (*n* = 1,250)		ADL Score[‡] (*n* = 2,974)		History of Falls[§] (*n* = 3,103)	
	Estimate (95% CI)	*p* Value	Estimate (95% CI)	*p* Value	Odds Ratio (95% CI)	*p* Value
Vestibular dysfunction	−3.4 (−5.2, −1.6)	<.0001	0.4 (0.2, 0.6)	.001	2.6 (1.2, 5.5)	.017
Female	4.9 (3.2, 6.6)	<.0001	0.5 (0.4, 0.7)	<.0001	2.0 (1.3, 3.2)	.004
Age	−0.7 (−0.8, −0.6)	<.001	0.04 (0.02, 0.05)	<.0001	1.0 (1.0, 1.0)	.767
Race/ethnicity						
White	Ref		Ref		Ref	
Black	−13.1 (−16.0, −10.2)	<.0001	0.06 (−0.1, 0.3)	.534	1.3 (0.7, 2.2)	.435
Mexican American	−8.2 (−10.6, −5.8)	<.0001	−0.4 (−0.7, −0.1)	.007	0.5 (0.2, 1.1)	.081
Other race	−6.9 (−11.0, −2.2)	.005	0.3 (−0.1, 0.6)	.148	1.3 (0.5, 3.9)	.577
Education						
<High school	Ref		Ref		Ref	
High school graduate	8.6 (5.7, 11.5)	<.0001	−0.4 (−0.6, −0.1)	.003	0.8 (0.4, 1.4)	.380
>High school	14.1 (12.5, 15.7)	<.0001	−0.9 (−1.1, −0.7)	<.0001	0.5 (0.3, 1.0)	.051
Smoking, number of pack years						
Never	Ref		Ref		Ref	
<20	0.6 (−1.3, 2.4)	.530	0.2 (0.002, 0.5)	.048	2.1 (1.1, 4.0)	.027
≥20	−0.4 (−2.6, 1.8)	.723	0.6 (0.3, 0.8)	<.0001	2.5 (2.6, 4.4)	.002
Unknown	−1.9 (−7.1, 3.3)	.468	−0.1 (−0.5, 0.4)	.693	0.3 (0.1, 1.9)	.201
Hypertension	−2.3 (−4.2, −0.3)	.022	0.3 (0.1, 0.5)	.004	2.0 (0.9, 4.1)	.076
Diabetes	−4.1 (−6.2, −1.9)	.001	−0.03 (−0.2, 0.2)	.723	0.7 (0.4, 1.4)	.304
Stroke	−3.5 (−8.1, 1.2)	.136	0.5 (0.2, 0.8)	.001	3.7 (1.7, 8.1)	.002
Visual acuity	−0.1 (−0.11, −0.04)	<.0001	0.002 (−0.004, 0.004)	.112	1.0 (1.0, 1.0)	.025

Notes: DSS = digit symbol substitution.

*Using NHANES 1999–2002 with population-adjusted weights.

[†] Model fit: R^2 = .3579.

[‡] Poisson regression model, ADL difficulty Index aggregated and scaled by summing performance on 19 activities of daily living. Responses to individual activities range from 1 (no impairment) to 4 (complete impairment). Data was rescaled by subtracting 19 from each observation to allow the index to have a minimum value of zero, ranging from 0 (no impairment) to 57 (complete impairment). Model fit: R^2 = .1633.

[§] Logistic regression model. Model fit: R^2: .1079.

attainment had significantly lower levels of ADL difficulty relative to whites and less educated individuals respectively. Additionally, we analyzed the association between vestibular dysfunction and history of falls (Table 2). As observed previously (1), we found that vestibular dysfunction was associated with a 2.6-fold increase in the odds of falling (95% CI 1.2, 5.5; *p* = .017). Other variables associated with a significantly increased odds of falling were female gender, smoking, history of stroke, and poorer visual acuity.

Further, we used structural equation modelling first to test the hypothesis that the association between age and lower cognitive performance is mediated by vestibular impairment. Structural equation modeling allows for the modeling of multiple outcomes simultaneously. We tested 2 regression models in parallel, the first with vestibular dysfunction as an intermediate outcome, and the second with cognitive function as a final outcome. This analysis allowed us to estimate the fraction of the association between age and cognitive function that was mediated by vestibular dysfunction. In adjusted analyses for both regression models, we observed that vestibular function mediated 8.8% of the association between age and DSS score (Figure 1A). We next evaluated a SEM that assessed the parallel mediation by vestibular dysfunction, visual acuity, and hearing thresholds on the association between age and DSS score in the smaller subset (Figure 1B). We observed in this model that vestibular function mediated 14.3% of the association between age and DSS score, which was greater than the observed percent mediation by visual acuity (12.9%) and by hearing (9.5%). This mediation effect is different from the one observed previously as only a subsample of the original data was included due to the smaller sample size of collected hearing loss data.

Additionally, we developed SEMs testing the hypothesis that vestibular dysfunction contributed to lower cognitive function, and this, in turn, resulted in falls and increased ADL difficulty (Figure 2). For these models, we evaluated overall model fit of these hypothesized pathways. We observed in this model that reduced cognitive performance mediated 16.9% of the association between vestibular function and ADL difficulty and 4.9% of the association between vestibular function and falls risk.

Discussion

These analyses offer compelling evidence of a strong association between vestibular function and cognitive function. The specific cognitive measure used in NHANES is the DSS score, a subtest of the WAIS III. The DSS test is thought to assess multiple cognitive domains including psychomotor speed, attention, visuospatial skills, associative learning, and memory (13,14). The most well-investigated of these is the association between vestibular function and visuospatial ability with emerging literature showing impairment in visuospatial tasks such as spatial navigation and spatial memory associated with vestibular disorders (6,15,16). In addition, work by Smith and colleagues further underscores the importance of the vestibular system not only in deficits of spatial navigation, but also in nonspatial functions such as object recognition memory (17,18). The current study extends these observations of cognitive impairment in patients with

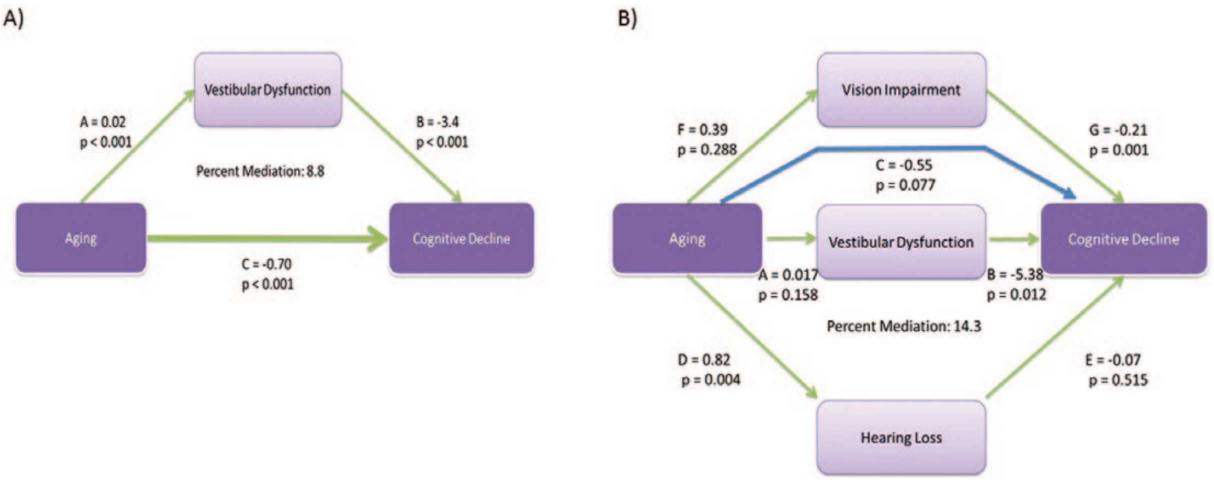

Figure 1. Structural equation model (SEM) of vestibular function as a partial mediator of the association between age and digit symbol substitution (DSS) score. All models are adjusted for race, gender, education, smoking status, hypertension, diabetes, stroke, and visual acuity. The percent mediation is calculated based on the formula: (A × B)/(A × B) + C, where A × B is the indirect effect of age on cognitive function mediated by vestibular function, C is the direct effect of age on cognitive function, and (A × B) + C is the total effect of age on cognitive function. (**A**) SEM of association between age, vestibular function, and DSS score. Vestibular function mediates 8.8% of the association between age and DSS score. (**B**) SEM of association between age, vestibular function, visual acuity, hearing level, and DSS score. Vestibular function mediates 14.3% of the association between age and DSS score, visual acuity mediates 12.9% of the association, and hearing level mediates 9.5% of the association.

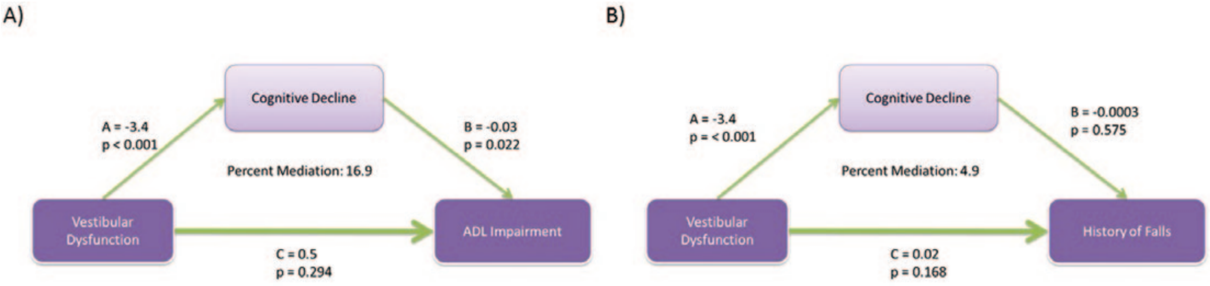

Figure 2. Structural equation models (SEMs) of digit symbol substitution (DSS) score as a partial mediator of the association between vestibular dysfunction and falls and ADL impairment. All models are adjusted for age, race, gender, education, smoking status, hypertension, diabetes, stroke, and visual acuity. The percent mediation is calculated based on the formula: (A × B)/((A × B) + C), where A × B is the indirect effect of vestibular dysfunction on falls or ADL impairment mediated by DSS score, C is the direct effect of vestibular dysfunction on falls or ADL impairment, and (A × B) + C is the total effect of vestibular dysfunction on falls or ADL impairment. (**A**) SEM of association between vestibular dysfunction, DSS score, and ADL impairment. (**B**) SEM of association between vestibular dysfunction, DSS score, and history of falls.

rare vestibular disorders, and suggests that vestibular loss associated with aging may contribute to the far more common cognitive deficits observed in older individuals. Indeed, it has been hypothesized that vestibular loss contributes to the onset of Alzheimer's disease (19), and one small study of 25 older adults observed a weak association between vestibular dysfunction and topographical memory impairment, one of the earliest signs of Alzheimer's disease (20). In this study, we found that vestibular dysfunction mediates 14.3% of the association between age and lower cognitive performance. Visual acuity was also significantly associated with lower DSS scores in multivariable regression modeling, although the partial mediation by vestibular dysfunction was greater than the mediation by visual acuity (12.9%) or by hearing (9.5%). This may relate to the broad influence of vestibular function on the cognitive processes associated with both spatial and nonspatial domains of cognition as discussed previously. In contrast, decreases in visual acuity have been suggested to be primarily related to a decline in the cognitive domain of verbal and nonverbal memory (21), whereas hearing loss has been suggested to primarily affect the cognitive domains of language as well as memory (22).

We further observed that the lower cognitive performance related to vestibular loss was associated with an increase in the odds of falling, and in ADL difficulty. Individuals with vestibular loss have been shown to have impairments in the ability to generate internal representations of their external world (23). As such, they have difficulty remembering the locations of previously seen targets, and navigating towards these targets or back to their starting locations (16). This inability to generate mental maps of the environment may make it difficult for patients with vestibular loss to transfer from the edge of the bed to the floor or to navigate around obstacles in their way, leading to falls and fall-related hip and wrist fractures (24). Indeed, a landmark study that video-documented over 200 falls in a long-term care facility observed that most falls were due to incorrect weight-shifting leading to dangerous transfers, followed by trips or stumbles over objects (25). As a result, the association of vestibular dysfunction with poorer cognitive outcomes is even more concerning as intact cognitive function is necessary to potentiate risk of falls in older adults (26).

Furthermore, impairment in the ability to carry out ADLs is a well-known sequela of cognitive decline (27). Reduction in the ability to spatially interact with one's environment may have implications for instrumental ADL's, including shopping and travelling in the community, and also basic ADL's, including transferring. ADL impairment is a fundamental risk factor for loss of independence and need for institutionalization, and is an outcome of age-related vestibular loss that has profound individual and societal-level implications. Additionally, ADL impairment has also been shown to have an independent impact on subsequent and rapid decline in cognitive function, contributing to a vicious circle that further increases risk of falls in this patient population (28).

The mechanisms by which vestibular dysfunction is associated with cognitive dysfunction are unclear, although several potential pathways have been hypothesized. Loss of peripheral vestibular input may lead to atrophy of areas within the cortical vestibular network, which notably includes the dorsal thalamus, the temporo-parietal junction, and the hippocampus. Atrophy of these structures may in turn result in impairments in visuospatial memory and perception (29–31). Indeed, a study of 10 patients with bilateral vestibular failure found that these patients developed significant hippocampal atrophy, and associated impairments in visuospatial tasks such as navigation in a virtual maze (6). Alternatively, the association between vestibular and cognitive dysfunction may relate to a reduction in cognitive resources available in the setting of vestibular loss. According to Kahneman's Capacity Model of Attention, an individual has a set amount of attention and cognitive resources available to allocate to mental tasks. The increased instability in gaze and posture associated with vestibular loss may require that increased attentional resources be allocated by the brain to maintaining balance and orientation (32). This leads to decreased cognitive reserve available for other tasks, particularly those that require processing by similar cognitive networks. Finally, vestibular dysfunction has been associated with affective disorders such as anxiety and depression, which may in turn contribute to cognitive dysfunction (33).

Limitations of this study include the cross-sectional and correlational nature of the analyses, which cannot support causal inferences. Additionally, the cross-sectional study design may have underestimated the cognitive impact of vestibular dysfunction, which may be more accurately assessed through a longitudinal study in which the subjects' baseline performance is included as a covariate. Moreover, true mediation using SEMs cannot be assessed in these cross-sectional data as mediation implies temporality. As a result, the positive findings of our SEM models are primarily hypothesis-generating and serve to justify further study into a causal relationship between vestibular dysfunction and lower cognitive performance. Additionally, we have attempted to minimize the effects of confounding variables by adjusting for potential predictors of vestibular and cognitive dysfunction including age, gender, race, educational level, visual acuity, hearing function, and cardiovascular risk factors in our analyses. Furthermore, a causal association between loss of vestibular sensitivity and lower cognitive performance may be more plausible than the reverse, although we do note recent work suggesting bidirectional interactions whereby the cognitive state can influence vestibular responsivity (34).

Another limitation relates to the use of condition 4 of the modified Romberg test as a measure of vestibular function. This measure has been shown to approximate computerized dynamic posturography (CDP) testing, which is one of the instruments used in the clinical diagnosis of vestibular dysfunction (35). Posturography, as well as test condition 4 in this study, assesses a patient's ability to maintain balance when vestibular information is the only reliable sensory input (ie, in the absence of parallel visual and proprioceptive cues). Effective use of vestibular information requires appropriately receiving and processing vestibular input and making compensatory postural (musculoskeletal) changes (36,37). Postural tests may be affected by a participant's strength and musculoskeletal status (eg, presence of arthritis) as well as by motivational and volitional factors which may affect test compliance (38). However, in this study, these considerations may be mitigated by the fact that participants were only tested in condition 4 if they were able to pass the three prior conditions. As such, given the technical complexity of vestibular physiological testing the Romberg on foam with eyes closed test is one of the few objective proxies of vestibular function available in a nationally representative study and has been used extensively as a limited, though acceptable measure of vestibular function in the literature (39). The binary nature of this predictor variable also precludes analyses based on degree of severity of vestibular dysfunction. Lastly, the DSS was the only measure of cognitive performance included in NHANES, which preclude generalization of the results to global cognitive function. However, as discussed previously, it has been shown to have a high sensitivity for cognitive impairment across a wide range of tasks, including psychomotor speed, sustained attention, visual spatial skills, associative learning, and memory. As such, it is considered a more sensitive measure of dementia than the widely used Mini-mental status exam in assessing the presence of cognitive impairment and changes in cognition in individuals with high to medium levels of cognitive function, as was the case with the study population in NHANES (40).

We observed in this study a significant independent association between vestibular function and cognitive function, which was also significantly impacted by other health risk factors, including history of hypertension, diabetes, and poorer visual acuity. Moreover, we demonstrated that vestibular function is an important mediator of the association between age and lower cognitive performance. Finally, we propose and test a hypothesis that vestibular impairment contributes to worse cognitive outcomes, which in turn may result in critical adverse geriatric outcomes including falls and ADL difficulty. These findings have potentially profound public health implications, given the widespread and devastating effects of age-related cognitive decline to affected individuals and to society. Future studies will need to establish whether mitigating age-related decline in vestibular sensitivity will forestall these highly morbid and costly outcomes.

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Conflict of Interest

None declared.

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