

1 Sensory system-specific associations between brain structure 2 and balance

3 KE Hupfeld^a, HR McGregor^a, CJ Hass^a, O Pasternak^b, RD Seidler^{a,c,*}

4 ^a*Department of Applied Physiology and Kinesiology, University of Florida, Gainesville, FL, USA*

5 ^b*Departments of Psychiatry and Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston,
6 MA, USA*

7 ^c*University of Florida Norman Fixel Institute for Neurological Diseases, Gainesville, FL, USA*

8 **Abstract**

9 Nearly 75% of older adults in the United States report balance problems. Balance difficulties
10 are more pronounced during sensory feedback perturbation (e.g., standing with the eyes closed
11 or on foam). Although it is known that aging results in widespread brain atrophy, less is known
12 about how brain structure relates to balance performance under varied sensory conditions in
13 older age. We measured postural sway of 36 young (18-34 years) and 22 older (66-84 years)
14 adults during four conditions: eyes open, eyes closed, eyes open on foam, and eyes closed on
15 foam. We calculated three summary measures indicating visual, proprioceptive, and vestibular
16 contributions to balance. We also collected T_1 -weighted and diffusion-weighted anatomical MRI
17 scans. We aimed to: 1) test for age group differences in brain structure-balance relationships
18 across a range of structural brain measures (i.e., volumetric, surface, and white matter mi-
19 crostructure); and 2) assess how brain structure measures relate to balance, regardless of age.
20 Across both age groups, thinner cortex in multisensory integration regions was associated with
21 greater reliance on visual inputs for balance. Greater gyration within sensorimotor and pari-
22 etal cortices was associated with greater reliance on proprioceptive inputs for balance. Poorer
23 vestibular function was correlated with thinner vestibular cortex, greater gyration within sen-
24 sorimotor, parietal, and frontal cortices, and lower free water-corrected axial diffusivity in the
25 superior-posterior corona radiata and across the corpus callosum. These results contribute to
26 our scientific understanding of how individual differences in brain structure relate to balance.
27 This has implications for developing brain stimulation interventions to improve balance.

*Corresponding Author: rachaelseidler@ufl.edu

28 **Significance Statement**

29 Older age is associated with greater postural sway, particularly when sensory information is
30 perturbed (e.g., by closing one's eyes). Our work contributes to the field by identifying how indi-
31 vidual differences in regional brain structure relate to balance under varying sensory conditions
32 in young and older adults. Across both age groups, lower cortical thickness in sensory inte-
33 gration and vestibular regions, greater gyrification within sensorimotor, parietal, and temporal
34 regions, and lower free water-corrected axial diffusivity in the corpus callosum and corona radi-
35 ata were related to individual differences in balance scores. We identified brain structures that
36 are associated with specific sensory balance scores; therefore, these results have implications
37 for which brain regions to target in future interventions for different populations.

38 Introduction

39 Balance control declines with older age (e.g., Abrahamova and Hlavačka 2008; Choy et al.
40 2003; Colledge et al. 1994; Røgind et al. 2003), and nearly 75% of individuals over the age
41 of 70 in the United States report balance problems (Dillon, 2010). While there are age-related
42 declines to both the peripheral musculoskeletal system (Boelens et al., 2013) and spinal reflexes
43 (Baudry and Duchateau, 2012), degradation of brain structure and function with aging (Seidler
44 et al., 2010) likely also contributes to age-related balance declines. Indeed, studies measuring
45 brain function during standing balance using electroencephalography (Hülsdünker et al., 2015;
46 Varghese et al., 2015) and transcranial magnetic stimulation (TMS; Ackermann et al., 1991;
47 Nakazawa et al., 2003) support cortical contributions to balance control (for review, see: Jacobs
48 and Horak 2007; Papegaaij et al. 2014a; Taube et al. 2008).

49 Postural control is affected by the availability of visual, proprioceptive, and vestibular inputs,
50 which are integrated to signal the body's orientation and configuration in space (Horak, 2006;
51 Leibowitz and Shupert, 1985; Mahboobin et al., 2005; Peterka, 2002; Shumway-Cook and Ho-
52 rak, 1986). Each of these sensory systems is subject to age-related declines (e.g., reduced re-
53 ceptor numbers; Maki et al. 1999; Patel et al. 2009), and aging also disrupts the relative weight-
54 ing and integration of their inputs (Colledge et al., 1994; Stelmach et al., 1989; Teasdale et al.,
55 1991; Woollacott et al., 1986). Compared to young adults, older adults experience relatively
56 greater difficulty maintaining their balance during sensory feedback perturbations (e.g., stand-
57 ing with the eyes closed or on foam; Alhanti et al. 1997; Choy et al. 2003; Judge et al. 1995).
58 Here we examined balance across four conditions with varied sensory inputs (i.e., eyes open
59 (EO), eyes closed (EC), eyes open-foam (EOF), and eyes closed-foam (ECF)). This allowed us
60 to characterize individual differences in reliance on visual, proprioceptive, and vestibular inputs.

61 There is some evidence that brain neurochemistry and function influence balance in older
62 age. For instance, positron emission tomography (PET) measures of striatal dopaminergic den-
63 ervation (Cham et al., 2007), genetic markers related to dopaminergic transmission (Hupfeld
64 et al., 2018), magnetic resonance spectroscopy metrics of brain antioxidant (glutathione) levels
65 (Hupfeld et al., 2021c), and TMS measures of γ -aminobutyric acid (GABA) (Papegaaij et al.,

66 2014b) all correlate with balance performance in older adults. Moreover, functional near-infrared
67 spectroscopy (fNIRS) studies have revealed increased prefrontal brain activity for older adults
68 during standing versus sitting (Mahoney et al., 2016), and increased occipital, frontal, and
69 vestibular cortical activity in older adults during increasingly difficult balance conditions (Lin
70 et al., 2017). These studies provide important insight into the neurochemical and functional
71 correlates of balance control in aging. However, it is widely held that age differences in brain
72 function are at least partially driven by structural brain atrophy (Papegaaij et al., 2014a). Thus,
73 it is important to also understand how individual and age differences in brain structure relate to
74 balance.

75 Studies of brain structure have shown that poorer balance balance performance in older
76 adults has been linked to larger ventricles (Sullivan et al., 2009; Tell et al., 1998), greater
77 white matter hyperintensity burden (Starr et al., 2003; Sullivan et al., 2009), reduced white
78 matter fractional anisotropy in the corpus callosum (Sullivan et al., 2010; Van Impe et al., 2012),
79 and reduced gray matter volume in the basal ganglia, superior parietal cortex, and cerebellum
80 (Rosano et al., 2007). Other studies have reported no such associations between brain struc-
81 ture and balance in older adults (Ryberg et al., 2007) or opposite relationships between poorer
82 brain structure (e.g., lower basal ganglia gray matter volume) and *better* balance (Boisgontier
83 et al., 2017). Most previous studies investigating associations between brain structure and bal-
84 ance have used only one MRI modality or have focused solely on pathological markers (e.g.,
85 white matter hyperintensities instead of ‘normal-appearing’ white matter; Starr et al., 2003; Sul-
86 livan et al., 2009). Thus, while this prior work suggests a link between maintenance of brain
87 structure—particularly in sensorimotor regions—in aging and maintenance of postural control,
88 further studies are needed. Moreover, only limited prior work has examined brain structure
89 relationships with sensory-specific balance metrics (Van Impe et al., 2012), though identifying
90 such relationships has implications for better understanding the neural correlates of age-related
91 conditions such as peripheral neuropathy and vestibular dysfunction.

92 We previously reported on age group differences in brain structure in this cohort (Hupfeld
93 et al., 2021a). In the current study, we addressed two aims: First, we tested for age group dif-

94 differences in the relationship between brain structure and sensory-specific measures of standing
95 balance. As described above, since fNIRS studies show greater prefrontal brain activity for older
96 adults during balance versus sitting (Mahoney et al., 2016), we predicted that greater prefrontal
97 atrophy would correlate more strongly with worse balance scores for the older adults. Second,
98 we determined how sensory-specific measures of standing balance related to brain structure
99 across the whole sample, regardless of age. We hypothesized that, across both young and
100 older adults, we would see functionally specific brain structure-behavior associations in which
101 brain structure in the primary visual, somatosensory, and vestibular cortices would be associ-
102 ated with visual and proprioceptive reliance scores and vestibular function scores, respectively.

103 **Methods**

104 The University of Florida's Institutional Review Board provided approval for all procedures
105 performed in this study, and all individuals provided their written informed consent to participate.

106 **Participants**

107 37 young and 25 older adults participated in this study. Due to the COVID-19 global pan-
108 demic, data collection was terminated before we attained the planned sample size for older
109 adults. One young and one older adult were excluded from all analyses because their balance
110 data contained extreme outlier values (>5 standard deviations from the group mean). Two older
111 adults were excluded from analyses of the T_1 -weighted images: one participant's head did not
112 fit within the 64-channel coil, so a 20-channel coil was used instead, and we excluded their data
113 due to poor image quality. The other was excluded due to an incidental finding. T_1 -weighted
114 images from $n = 36$ young and $n = 22$ older adults were included in analyses. Due to time
115 constraints, diffusion MRI data were not collected for one additional young and two additional
116 older adults; thus, diffusion MRI analyses included data from $n = 35$ young and $n = 20$ older
117 adults.

118 We screened participants for MRI eligibility and, as part of the larger study, TMS eligibility.
119 We excluded those with MRI or TMS contraindications (e.g., implanted metal, claustrophobia, or
120 pregnancy), history of a neurologic (e.g., stroke, Parkinson's disease, seizures, or a concussion

121 in the last six months) or psychiatric condition (e.g., active depression or bipolar disorder) or
122 treatment for alcoholism; self-reported smokers; and those who self-reported consuming more
123 than two alcoholic drinks per day on average. Participants were right-handed and were able to
124 stand for at least 30 seconds with their eyes closed. We screened participants for cognitive im-
125 pairment over the phone using the Telephone Interview for Cognitive Status (TICS-M; de Jager
126 et al., 2003) and excluded those who scored less than 21 of 39 points (which is equivalent
127 to scoring less than 25 points on the Mini-Mental State Exam and indicates probable cogni-
128 tive impairment (de Jager et al., 2003)). During the first session, we re-screened participants
129 for cognitive impairment using the Montreal Cognitive Assessment (MoCA; Nasreddine et al.
130 2005). We planned to exclude individuals if they scored less than 23 of 30 points (Carson et al.,
131 2018), but none were excluded for this reason.

132 **Testing Sessions**

133 We first collected information on demographics (e.g., age, sex, and years of education),
134 self-reported medical history, handedness, footedness, exercise, and sleep. We also collected
135 anthropometric information (e.g., height, weight, and leg length). Participants completed bal-
136 ance testing, followed by an MRI scan approximately one week later. For 24 hours prior to each
137 session, participants were asked not to consume alcohol, nicotine, or any drugs other than the
138 medications they disclosed to us. At the start of each session, participants completed the Stan-
139 ford Sleepiness Questionnaire, which asks about the number of hours slept the previous night
140 and a current sleepiness rating (Hoddes et al., 1972).

141 **Balance Testing**

142 Participants completed four balance conditions while instrumented with six Opal inertial
143 measurement units (IMUs; v2; ADPM Wearable Technologies, Inc., Portland, OR, USA). IMUs
144 were placed on the feet, wrists, around the waist at the level of the lumbar spine, and across
145 the torso at the level of the sternal angle. Only the lumbar IMU was used to measure postural
146 sway during standing balance. Participants completed the four-part Modified Clinical Test of
147 Sensory Interaction in Balance (mCTSIB). The mCTSIB has established validity in young and

148 older adults (Alhanti et al., 1997; Cohen et al., 1993; Teasdale et al., 1991) and high retest
149 and inter-tester reliability (Dawson et al., 2018). Participants faced a blank white wall and were
150 instructed to stand as still as possible and refrain from talking for four 30-second trials:

151 1. eyes open (EO): unperturbed visual, proprioceptive, and vestibular inputs

152 2. eyes closed (EC): visual input is removed, while proprioceptive and vestibular inputs re-
153 main unperturbed

154 3. eyes open - foam surface (EOF): the foam surface manipulates proprioceptive inputs, but
155 visual and vestibular inputs remain unperturbed

156 4. eyes closed - foam surface (ECF): visual and proprioceptive cues are compromised, and
157 only vestibular cues are unperturbed

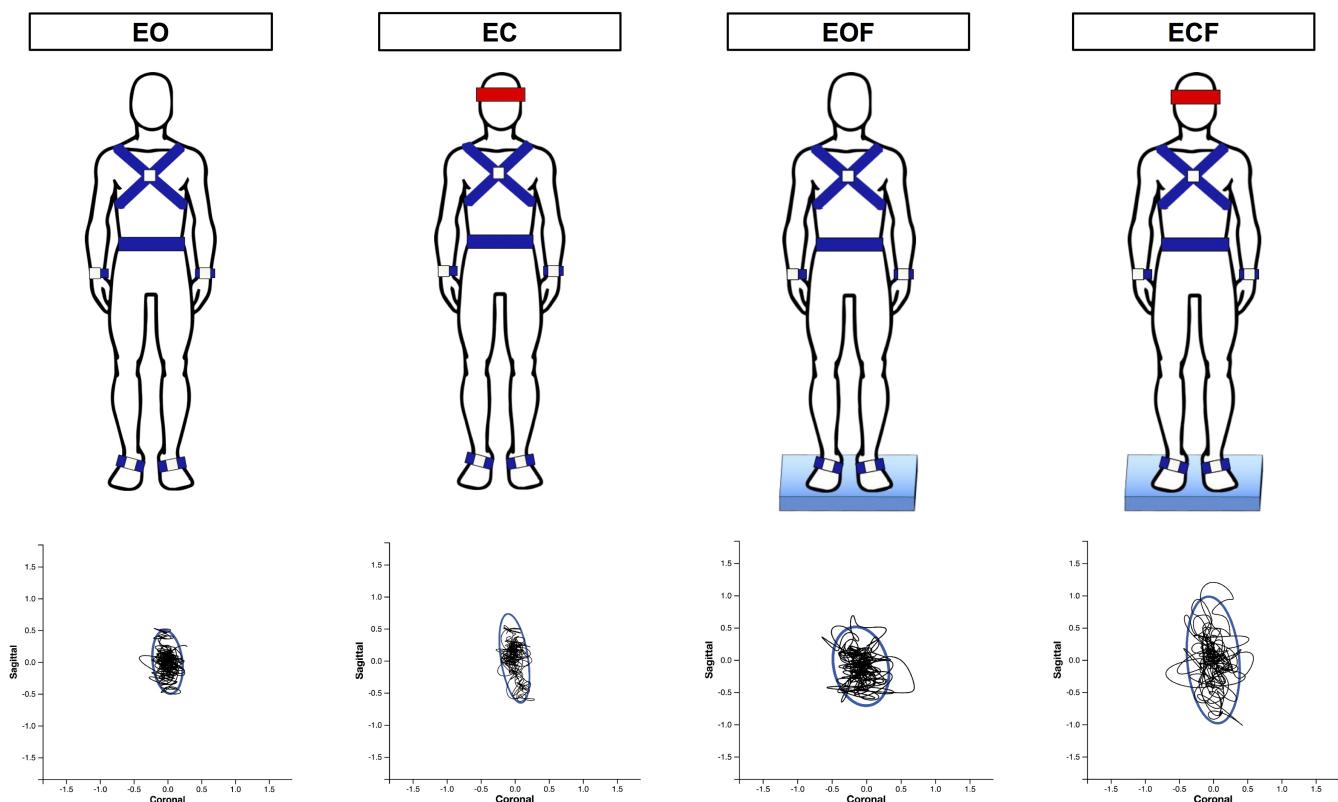


Figure 1: mCTSIB balance conditions. Participants completed four 30-second trials: eyes open (EO), eyes closed (EC), eyes open-foam (EOF), and eyes closed-foam (ECF). Postural sway from each condition was used to calculate the three balance outcome variables, i.e., the visual reliance, proprioceptive reliance, and vestibular function scores. Bottom. Here we depict the sway path (black line) and area (blue oval) for each condition for an exemplar young adult participant. This individual showed greater postural sway as the conditions progressed.

158 We recorded inertial data during the four trials using MobilityLab software. MobilityLab calcu-
159 lated 25 spatiotemporal features of postural sway using the iSway algorithm (Mancini et al.,
160 2012). We then calculated three summary scores using the 95% ellipse sway area (m^2/s^4) vari-
161 able (i.e., the area of an ellipse covering 95% of the sway trajectory in the coronal and sagittal
162 planes) from each of the four conditions (Fig. 1). Greater postural sway is interpreted as "worse"
163 standing balance performance (Dewey et al., 2020), as greater postural sway is typically higher
164 for older compared with young adults (e.g., Abrahamova and Hlavačka, 2008; Colledge et al.,
165 1994; Røgind et al., 2003) and is linked to higher risk of falls (e.g., Laughton et al., 2003; Maki
166 et al., 1994).

The visual reliance score represents the percent change in postural sway between the eyes closed and the eyes open conditions (considering the foam and firm surface conditions independently and taking the minimum score of the two). Higher scores indicate more difficulty standing still in the absence of visual input. A higher visual reliance score is the result of poorer performance (i.e., more postural sway) during the eyes closed conditions and/or better performance on the eyes open conditions (i.e., less postural sway). Thus, a higher score suggests that the individual is more "reliant" on visual input for balance.

$$Visual\ Reliance\ Score = \min\left[\left(\frac{EC - EO}{EO}\right) * 100, \left(\frac{ECF - EOF}{EOF}\right) * 100\right]$$

The proprioceptive reliance score represents the percent change between the foam and the firm surface conditions (considering the eyes open and eyes closed conditions independently and taking the minimum of score of the two). Higher scores indicate more difficulty standing still with compromised proprioceptive input. A higher proprioceptive reliance score is the result of poorer performance (i.e., more postural sway) on the foam conditions and/or better performance on the firm surface conditions (i.e., less postural sway). Thus, a higher score suggests that the individual is more "reliant" on proprioceptive input for balance.

$$Proprioceptive\ Reliance\ Score = \min\left[\left(\frac{EOF - EO}{EO}\right) * 100, \left(\frac{ECF - EC}{EO}\right) * 100\right]$$

The vestibular function score represents the percent change between the ECF and EO conditions. Higher scores indicate more difficulty standing still when only vestibular input is appropriate and visual / proprioceptive inputs are compromised. Contrary to the scores described above (which represent reliance on visual and proprioceptive inputs, respectively), higher scores here indicate *poorer* vestibular function (Dewey et al., 2020).

$$Vestibular\ Function\ Score = \left(\frac{ECF - EO}{EO} \right) * 100$$

167 These formulas represent those recommended by APDM (the IMU company) for calculating
168 mCTSIB summary scores (for further details, see: <https://support.apdm.com/hc/en-us/articles/217035886-How-are-the-ICTSIB-composite-scores-computed->). For simplicity
169 and to keep with prior literature (Goble et al., 2019, 2020), we will use the interpretation of
170 higher visual and proprioceptive scores indicating more "reliance" on these two sensory sys-
171 tems for balance. However, it is worth noting that this interpretation might be oversimplified.
172 These scores may also index sensory reweighting and integration more so than reliance on a
173 single sensory modality (Kalron, 2017). We expand on this in the Discussion.

175 ***MRI Scan***

176 We used a Siemens MAGNETOM Prisma 3 T scanner (Siemens Healthcare, Erlangen,
177 Germany) with a 64-channel head coil to collect T_1 -weighted and diffusion-weighted scans for
178 each participant. We collected the 3D T_1 -weighted anatomical image using a magnetization-
179 prepared rapid gradient-echo (MPRAGE) sequence. The parameters were: repetition time (TR)
180 = 2000 ms, echo time (TE) = 3.06 ms, flip angle = 8°, field of view = 256 × 256 mm², slice
181 thickness = 0.8 mm, 208 slices, voxel size = 0.8 mm³. Next, we collected the diffusion-weighted
182 spin-echo prepared echo-planar imaging sequence with the following parameters: 5 b_0 volumes
183 (without diffusion weighting) and 64 gradient directions with diffusion weighting 1000 s/mm²,
184 TR = 6400 ms, TE = 58 ms, isotropic resolution = 2 × 2 × 2 mm, FOV = 256 × 256 mm², 69
185 slices, phase encoding direction = Anterior to Posterior. Immediately prior to this acquisition, we
186 collected 5 b_0 volumes (without diffusion weighting) in the opposite phase encoding direction

187 (Posterior to Anterior) for later use in distortion correction.

188 ***T₁-Weighted Image Processing for Voxelwise Analyses***

189 We used the same T_1 -weighted processing steps as described in our previous work (Hupfeld
190 et al., 2021a).

191 *Gray matter volume*

192 We processed the T_1 -weighted scans using the Computational Anatomy Toolbox (CAT12;
193 version r1725; Gaser et al., 2016; Gaser and Kurth, 2017) in MATLAB R2019b. We imple-
194 mented default CAT12 preprocessing steps. This included segmentation into gray matter, white
195 matter, and cerebrospinal fluid, followed by spatial normalization to standard space using high-
196 dimensional Dartel registration and modulation. Modulation involves multiplying the normalized
197 gray matter segment by its corresponding Jacobian determinant to produce modulated gray
198 matter volume images in standard space. The Jacobian determinant encodes local shrinkage
199 and expansion between subject space and the target image (i.e., standard space template). To
200 increase signal-to-noise ratio, we smoothed the modulated, normalized gray matter segments
201 using Statistical Parametric Mapping 12 (SPM12, v7771; Ashburner et al., 2014) with an 8 mm
202 full width at half maximum kernel. We entered the smoothed, modulated, normalized gray mat-
203 ter volume maps into the group-level voxelwise statistical models described below. We used
204 CAT12 to calculate total intracranial volume for each participant for later use as a covariate in
205 our group-level statistical analyses.

206 *Cortical surface metrics*

207 The CAT12 pipeline also extracts surface-based voxelwise morphometry metrics (Dahnke
208 et al., 2013; Yotter et al., 2011a) using a projection-based thickness algorithm that handles
209 partial volume information, sulcal blurring, and sulcal asymmetries without explicit sulcus re-
210 construction (Dahnke et al., 2013; Yotter et al., 2011a). We extracted four surface metrics: 1)
211 cortical thickness: the width of the cortical gray matter between the outer surface (i.e., the gray
212 matter-cerebrospinal fluid boundary) and the inner surface (i.e., the gray matter-white matter
213 boundary) (Dahnke et al., 2013); 2) cortical complexity: fractal dimension, a metric of folding

214 complexity of the cortex (Yotter et al., 2011b); 3) sulcal depth: the Euclidean distance between
215 the central surface and its convex hull (Yun et al., 2013); and 4) gyration index: a metric
216 based on the absolute mean curvature, which quantifies the amount of cortex buried within the
217 sulcal folds as opposed to the amount of cortex on the “outer” visible surface (Luders et al.,
218 2006). We resampled and smoothed the surfaces at 15 mm for cortical thickness and 20 mm
219 for the three other metrics. We entered these resampled and smoothed surface files into our
220 group-level voxelwise statistical models.

221 *Cerebellar volume*

222 Similar to our past work (Hupfeld et al., 2021b; Salazar et al., 2020, 2021), we applied
223 specialized preprocessing steps to the cerebellum to produce cerebellar volume maps, with
224 improved normalization of the cerebellum (Diedrichsen, 2006; Diedrichsen et al., 2009). We
225 entered each participant’s whole-brain T_1 -weighted image into the CEREBellum Segmenta-
226 tion (CERES) pipeline (Romero et al., 2017). We used a binary mask from each participant’s
227 CERES cerebellar segmentation to extract their cerebellum from their whole-brain T_1 -weighted
228 image. We used rigid, affine, and Symmetric Normalization (SyN) transformation procedures in
229 the Advanced Normalization Tools package (ANTs; v1.9.17; Avants et al., 2010, 2011) to warp
230 (in a single step) each participant’s extracted subject space cerebellum to a 1 mm cerebellar
231 template in standard space, the Spatially Unbiased Infratentorial Template (SUIT) (Diedrichsen,
232 2006; Diedrichsen et al., 2009). The flowfields used to warp native cerebellar segments directly
233 to SUIT space were additionally used to calculate the Jacobian determinant image, using ANTs’
234 *CreateJacobianDeterminantImage.sh* function. We multiplied each normalized cerebellar seg-
235 ment by its corresponding Jacobian determinant to produce modulated cerebellar images in
236 standard space. To increase signal-to-noise ratio, we smoothed the modulated, normalized
237 cerebellar images using a kernel of 2 mm full width at half maximum and entered the resulting
238 cerebellar volume maps into our group-level voxelwise statistical models.

239 ***Diffusion-Weighted Image Processing for Voxelwise Analyses***

240 We used the same diffusion-weighted processing steps as described in detail in our previous
241 work (Hupfeld et al., 2021a).

242 *Diffusion preprocessing*

243 We corrected images for signal drift (Vos et al., 2017) using the ExploreDTI graphical toolbox
244 (v4.8.6; www.exploredti.com; Leemans et al., 2009) in MATLAB (R2019b). Next, we used the
245 FMRIB Software Library (FSL; v6.0.1; Jenkinson et al., 2012; Smith et al., 2004) processing
246 tool, *topup*, to estimate the susceptibility-induced off-resonance field (Andersson et al., 2003).
247 This yielded a single corrected field map for use in eddy current correction. We used FSL's
248 *eddy_cuda* to simultaneously correct the data for eddy current-induced distortions and both
249 inter- and intra-volume head movement (Andersson and Sotropoulos, 2016).

250 *FW correction and tensor fitting*

251 We implemented a custom free-water (FW) imaging algorithm (Pasternak et al., 2009) in
252 MATLAB. This algorithm estimates FW fractional volume and FW-corrected diffusivities by fitting
253 a two-compartment model at each voxel (Pasternak et al., 2009). The FW compartment reflects
254 the proportion of water molecules with unrestricted diffusion and is quantified by the fractional
255 volume of this compartment. FW fractional volume ranges from 0 to 1; FW = 1 indicates that
256 a voxel is filled with freely diffusing water molecules (e.g., within the ventricles). The tissue
257 compartment models FW-corrected indices of water molecule diffusion within or in the vicinity
258 of white matter tissue, quantified by diffusivity (FAt, RDt, and ADt). These metrics (FW, FAt,
259 RDt, ADt) are provided as separate voxelwise maps.

260 **Tract-Based Spatial Statistics**

261 We applied FSL's tract-based spatial statistics (TBSS) processing steps to prepare the data
262 for voxelwise analyses across participants (Smith et al., 2006). TBSS was selected because it
263 avoids problems associated with suboptimal image registration between participants and does
264 not require spatial smoothing. TBSS uses a carefully-tuned nonlinear registration and projec-
265 tion onto an alignment-invariant tract representation (i.e., the mean FA skeleton); this process
266 improves the sensitivity, objectivity, and interpretability of analyses of multi-subject diffusion
267 studies. We used the TBSS pipeline as provided in FSL. This involves eroding the FA images
268 slightly and zeroing the end slices, then bringing each subject's FA data into standard space

269 using the nonlinear registration tool FNIRT (Andersson et al., 2007b,a). A mean FA image is
270 then calculated and thinned to create a mean FA skeleton. Each participant's aligned FA data is
271 then projected onto the group mean skeleton. Lastly, we applied the same nonlinear registration
272 to the FW, FAt, RDt, and ADt maps to project these data onto the original mean FA skeleton.
273 Ultimately, these TBSS procedures resulted in skeletonized FW, FAt, ADt, and RDt maps in
274 standard space for each participant. These were the maps that we entered in our group-level
275 voxelwise statistical models.

276 **Ventricular Volume Calculation**

277 CAT12 automatically calculates the inverse warp, from standard space to subject space, for
278 the Neuromorphometrics (<http://Neuromorphometrics.com>) volume-based atlas. We isolated
279 the lateral ventricles from this atlas in subject space. We visually inspected the ventricle masks
280 overlaid onto each participant's T_1 -weighted image in ITK-SNAP and hand corrected the ROI
281 mask if needed (Yushkevich et al., 2006). Using *fs/stats*, we extracted the number of voxels
282 in each ventricular mask in subject space and calculated the mean image intensity within the
283 ventricles in the subject space cerebrospinal fluid segment. We then calculated each lateral
284 ventricular volume, in mL, as: (number of voxels in the ventricular mask)*(mean intensity of
285 the cerebrospinal fluid probabilistic map within the ROI mask)*(volume/voxel). In subsequent
286 statistical analyses, we used the average of the left and right side structures for each ROI,
287 and we entered these ROI volumes as a percentage of total intracranial volume to account for
288 differences in head size.

289 **Statistical Analyses**

290 *Participant characteristics, testing timeline, and balance*

291 We conducted all statistical analyses on the demographic and balance data using R (v4.0.0;
292 R Core Team, 2013). We conducted nonparametric two-sided Wilcoxon rank-sum tests for age
293 group differences in demographics, physical characteristics, and session timeline variables. We
294 used a Pearson chi-square test to check for differences in the sex distribution within each age
295 group. We used three linear models to test for age group differences in the balance scores (i.e.,

296 visual, proprioceptive, and vestibular), controlling for sex. We applied the Benjamini-Hochberg
297 false discovery rate (FDR) correction to the p values for the age group predictor (Benjamini and
298 Hochberg, 1995).

299 **Voxelwise Statistical Models**

300 We tested the same voxelwise models for each of the imaging modalities. In each case,
301 we defined the model using SPM12 and then re-estimated the model using the Threshold-Free
302 Cluster Enhancement toolbox (TFCE; <http://dbm.neuro.uni-jena.de/tfce>) with 5,000 per-
303 mutations. This toolbox provides non-parametric estimation using TFCE for models previously
304 estimated using SPM parametric designs. Statistical significance was determined at $p < 0.05$
305 (two-tailed) and family-wise error (FWE) corrected for multiple comparisons. In each of the be-
306 low models, we set the brain structure map as the outcome variable. In the gray matter volume
307 models only, we set the absolute masking threshold to 0.1 (Gaser and Kurth, 2017) and used
308 an explicit gray matter mask that excluded the cerebellum (because we analyzed cerebellar
309 volume separately from “whole brain” gray matter volume).

310 *Age group differences in brain structure*

311 We previously reported the results of two-sample t-tests for age group differences in brain
312 structure (Hupfeld et al., 2021a).

313 *Interaction of age group and balance scores*

314 First, we tested for regions in which the relationship between brain structure and balance
315 performance differed between young and older adults. We ran independent samples t-tests
316 and included the balance scores for young and older adults as covariates of interest. We tested
317 for regions in which the correlation between brain structure and balance performance differed
318 between young and older adults (i.e., for statistical significance in the interaction term). We con-
319 trolled for sex in all models and also for head size (i.e., total intracranial volume, as calculated
320 by CAT12) in the gray matter and cerebellar volume models.

321 *Whole group correlations of brain structure with balance scores*

322 Next, we conducted a linear regression omitting the age group*balance score interaction
323 term, to test for regions of association between brain structure and balance performance, re-
324 gardless of age or sex. That is, in each of these models, we included the whole cohort and
325 controlled for age and sex (but did not include an age group predictor or interaction term). In
326 the gray matter and cerebellar volume models, we also controlled for head size.

327 **Ventricular volume statistical models**

328 We carried out linear models in R to test for relationships between ventricular volume and
329 balance, controlling for age and sex. We then ran linear models testing for an interaction be-
330 tween age group and balance scores, controlling for sex. In each case, we FDR-corrected the
331 *p* values for the predictor of interest (i.e., balance score or the interaction term, respectively;
332 Benjamini and Hochberg, 1995).

333 **Multiple regression to fit the best model of vestibular function scores in older adults**

334 We used a stepwise multivariate linear regression to directly compare the predictive strength
335 of the brain structure correlates of balance scores identified by the analyses described above.
336 We ran one model for the vestibular function scores (as the visual and proprioceptive reliance
337 scores did not produce more than one resulting brain structure measure). We included as pre-
338 dictors age, sex and values from the peak result coordinate for each model that indicated a
339 statistically significant relationship between brain structure and vestibular function scores. We
340 used *stepAIC* (Venables et al., 1999) to produce a final model that retained only the best pre-
341 dictor variables; *stepAIC* selects a maximal model based on the combination of predictors that
342 produces the smallest Akaike information criterion (AIC). This stepwise regression approach
343 allowed us to fit the best model using brain structure to predict vestibular function scores.

344 **Results**

345 ***Age Differences in Participant Characteristics, Testing Timeline, and Balance***

346 There were no significant differences between the age groups for most demographic vari-
347 ables, including sex, handedness, footedness, and alcohol use (Table 1). The older adults had

348 higher body mass indices and exercised less compared to the young adults. The older adults
349 reported a greater fear of falling and less balance confidence. There were no age group differ-
350 ences in the number of days elapsed between the two testing sessions or in the difference in
351 start time for the sessions.

352 No age group differences emerged for visual reliance scores. That is, young and older
353 adults showed a similar increase in postural sway under the eyes closed compared to the eyes
354 open balance conditions (i.e., visual reliance score; Table 2; Fig. 2A). Older adults had higher
355 proprioceptive reliance compared to young adults, exhibiting greater postural sway during the
356 foam versus firm surface conditions (i.e., proprioceptive reliance score; Fig. 2B). Further, older
357 adults had poorer (i.e., higher) vestibular function scores compared to the young adults. That
358 is, older adults exhibited greater postural sway during the ECF versus EO conditions, indicating
359 poorer vestibular function (i.e., poorer performance when visual and proprioceptive inputs were
360 compromised and only vestibular input was available; Fig. 2C).

361

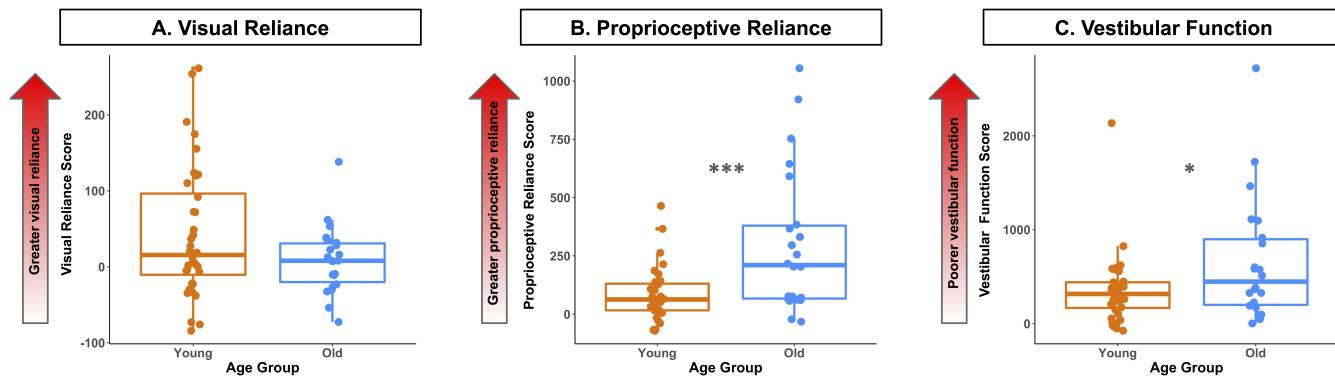


Figure 2: Age group differences in balance composite scores. Balance scores are shown for the older (blue) and younger (orange) adults. The red arrows point in the direction of higher scores. Higher scores indicate a greater reliance on visual (A) and proprioceptive (B) inputs for maintaining standing balance, or poorer vestibular function (C).

362 **Age Group Differences in Brain Structure**

363 Our recent publication provides a detailed report of age group differences in brain structure
364 in this cohort (Hupfeld et al., 2021a). Overall, we found evidence of widespread cortical and
365 cerebellar atrophy for older compared with young adults across the examined volumetric, sur-
366 face, white matter microstructure, and ventricle metrics. Interestingly, we identified the most
367 prominent age differences in several metrics (i.e., gray matter volume and cortical thickness) in

Table 1: Participant characteristics and testing timeline

Variables	Young adult median (IQR)	Older adult median (IQR)	W or χ^2	FDR corr. p	Effect size ^a
Demographics					
Sample size	36	22			
Age (years)	21.75 (2.36)	72.58 (9.72)			
Sex	19 F; 17 M	12 F; 10 M	0.02	0.896	
Physical characteristics and fitness					
Handedness laterality score ^b	85.17 (25.42)	100.00 (24.55)	329.50	0.423	-0.14
Footedness laterality score ^b	100.00 (22.22)	100.00 (138.39)	452.50	0.455	-0.13
Body mass index (kg/m ²)	22.76 (5.67)	25.92 (3.76)	175.00	0.006**	-0.46
Leisure-time physical activity ^c	46.00 (38.00)	29.00 (21.00)	551.00	0.017*	-0.37
Balance and fear of falling					
Balance confidence ^d	97.81 (3.61)	94.07 (4.38)	595.50	0.010**	-0.41
Fear of falling ^d	17.00 (3.00)	19.00 (2.00)	224.50	0.017*	-0.36
Education and cognition					
Years of education	15.00 (3.00)	16.00 (4.25)	226.00	0.017**	-0.35
MoCA score	28.00 (3.25)	27.00 (2.75)	517.50	0.114	-0.25
Alcohol use					
AUDIT score ^e	2.00 (3.50)	1.00 (3.75)	495.00	0.219	-0.21
Hours of sleep					
Behavioral session	7.00 (1.62)	7.50 (1.50)	343.00	0.656	-0.07
MRI session	7.00 (1.62)	7.00 (1.00)	319.50	0.382	-0.16
Testing timeline^f					
Behavioral vs. MRI session (days)	3.50 (6.25)	4.50 (4.75)	357.00	0.656	-0.08
Behavioral vs. MRI start (hours)	1.33 (1.41)	1.23 (1.10)	419.50	0.767	-0.05

Note: In the second and third columns, we report the median \pm interquartile range (IQR) for each age group in all cases except for sex. For sex, we report the number of males and females in each age group. In the fourth and fifth columns, for all variables except sex, we report the result of a nonparametric two-sample, two-sided Wilcoxon rank-sum test. For sex, we report the result of a Pearson's chi-square test for differences in the sex distribution within each age group. All participants with T_1 -weighted scans are included in the comparisons in this table. However, we excluded several individuals from the diffusion-weighted image analyses (see Methods). P values were FDR-corrected (Benjamini and Hochberg, 1995) across all models included in this table. * $p<0.05$, ** $p<0.01$. Significant p values are bolded.

^aIn the sixth column, we report the nonparametric effect size as described by (Rosenthal et al., 1994; Field et al., 2012).

^bWe calculated handedness and footedness laterality scores using two self-report surveys: the Edinburgh Handedness Inventory (Oldfield, 1971) and the Waterloo Footedness Questionnaire (Elias et al., 1998).

^cWe assessed self-reported physical activity using the Godin Leisure-Time Exercise Questionnaire (Godin et al., 1985).

^dParticipants self-reported Activities-Specific Balance Confidence scores (Powell and Myers, 1995) and fear of falling using the Falls Efficacy Scale (Tinetti et al., 1990).

^eParticipants self-reported alcohol use on the Alcohol Use Disorders Identification Test (AUDIT; Piccinelli, 1998).

^fHere we report the days between the testing sessions and the hours between the start time of the testing sessions.

Table 2: Age differences in balance scores

Mean (SD)		Predictors	Estimates (SE)	t	FDR Corr. <i>p</i>	<i>R</i> ²
Visual reliance Young: 42.89 (86.99)	Old: 8.71 (44.44)	(<i>Intercept</i>)	42.55 (12.41)	3.43		
		Age group (<i>Old</i>)	-34.39 (20.13)	-1.71	0.093	
		Sex (<i>Male</i>)	6.01 (9.79)	0.61		0.06
Proprioceptive reliance Young: 82.07 (115.39)	Old: 301.56 (308.63)	(<i>Intercept</i>)	82.64 (35.28)	2.34		
		Age group (<i>Old</i>)	219.85 (57.24)	3.84	<0.001***	
		Sex (<i>Male</i>)	-10.21 (27.84)	-0.37		0.21
Vestibular function Young: 348.75 (373.56)	Old: 654.36 (655.86)	(<i>Intercept</i>)	348.78 (83.92)	4.16		
		Age group (<i>Old</i>)	305.64 (136.15)	2.25	0.043*	
		Sex (<i>Male</i>)	-0.63 (66.22)	-0.01		0.08

Note: On the left side, we report mean (standard deviation) for the young and older age groups. On the right side, we report the results of three linear models testing for age group differences in each balance score, controlling for sex. *P* values for the age group predictor were FDR-corrected (Benjamini and Hochberg, 1995). SD = standard deviation; SE = standard error. **p*_{FDR-corr} < 0.05, ****p*_{FDR-corr} < 0.001. Significant *p* values are bolded.

368 the sensorimotor cortices, and comparatively less age difference in these metrics in the frontal
369 cortices. Refer to Hupfeld et al. (2021a) for further details.

370 **No Age Differences in the Relationship of Brain Structure with Balance**

371 Across all brain structure metrics, there were no age differences in the relationship between
372 the balance scores and brain structure. That is, there was no interaction of age group and
373 balance scores; therefore, our second set of statistical analyses did not include an interaction
374 term and instead aimed to identify relationships between brain structure and balance scores
375 across the whole cohort (regardless of age).

376 **Brain Structure Correlates of Balance Scores**

377 There were no relationships between gray matter volume, cortical complexity, sulcal depth,
378 or cerebellar volume and balance performance across the whole cohort. Thinner cortex (i.e.,
379 "worse" brain structure) within a region encompassing portions of the right cingulate gyrus (isth-
380 mus), precuneus, and lingual gyrus was associated with higher visual reliance scores (Fig. 3;
381 Table 3). That is, those individuals who had the thinnest cortex in these regions also showed
382 the greatest increase in postural sway between conditions with the eyes closed compared with
383 open (indicating greater reliance on visual inputs for balance). In addition, thinner cortex within
384 two regions encompassing portions of the left supramarginal and postcentral gyri and the bank
385 of the left superior temporal sulcus was associated with poorer vestibular function scores (Fig.
386 3; Table 3). That is, those individuals who had the thinnest cortex in these regions also exhibited
387 the most postural sway during the ECF relative to the EO condition (indicating poorer vestibular
388 function).

Table 3: Regions of correlation between cortical thickness and balance scores

Region	Overlap of Atlas Region	TFCE Level	
		Extent (k_E)	$p_{FWE-corr}$
Visual reliance			
R cingulate gyrus (isthmus)	43%	344	0.030*
R precuneus	39%	—	—
R lingual gyrus	15%	—	—
R pericalcarine cortex	1%	—	—
Vestibular function			
L supramarginal gyrus	69%	188	0.038*
L postcentral gyrus	31%	—	—
L superior temporal sulcus (bank)	100%	55	0.049*

Note: Here we list all atlas regions from the Desikan-Killiany DK40 atlas (Desikan et al., 2006) that overlapped with each resulting cluster. We do not list volumetric (e.g., MNI space) coordinates in this table because volumetric coordinates cannot be mapped directly onto cortical surfaces. L = left; R = right. $*p_{FWE-corr} < 0.05$. Significant p values are bolded.

389 Higher gyration index (i.e., "better" brain structure; Luders et al., 2006) within two large
390 clusters encompassing portions of the left sensorimotor, parietal, supramarginal, paracentral,
391 and frontal cortices and precuneus was associated with higher proprioceptive reliance scores
392 (Fig. 4; Table 4). That is, those individuals with the highest gyration index in these regions
393 also showed the greatest increase in postural sway for conditions using the foam compared to
394 the firm surfaces (indicating greater reliance on proprioceptive inputs for balance).
395 In addition, higher gyration index within a large region spanning portions of the frontal,

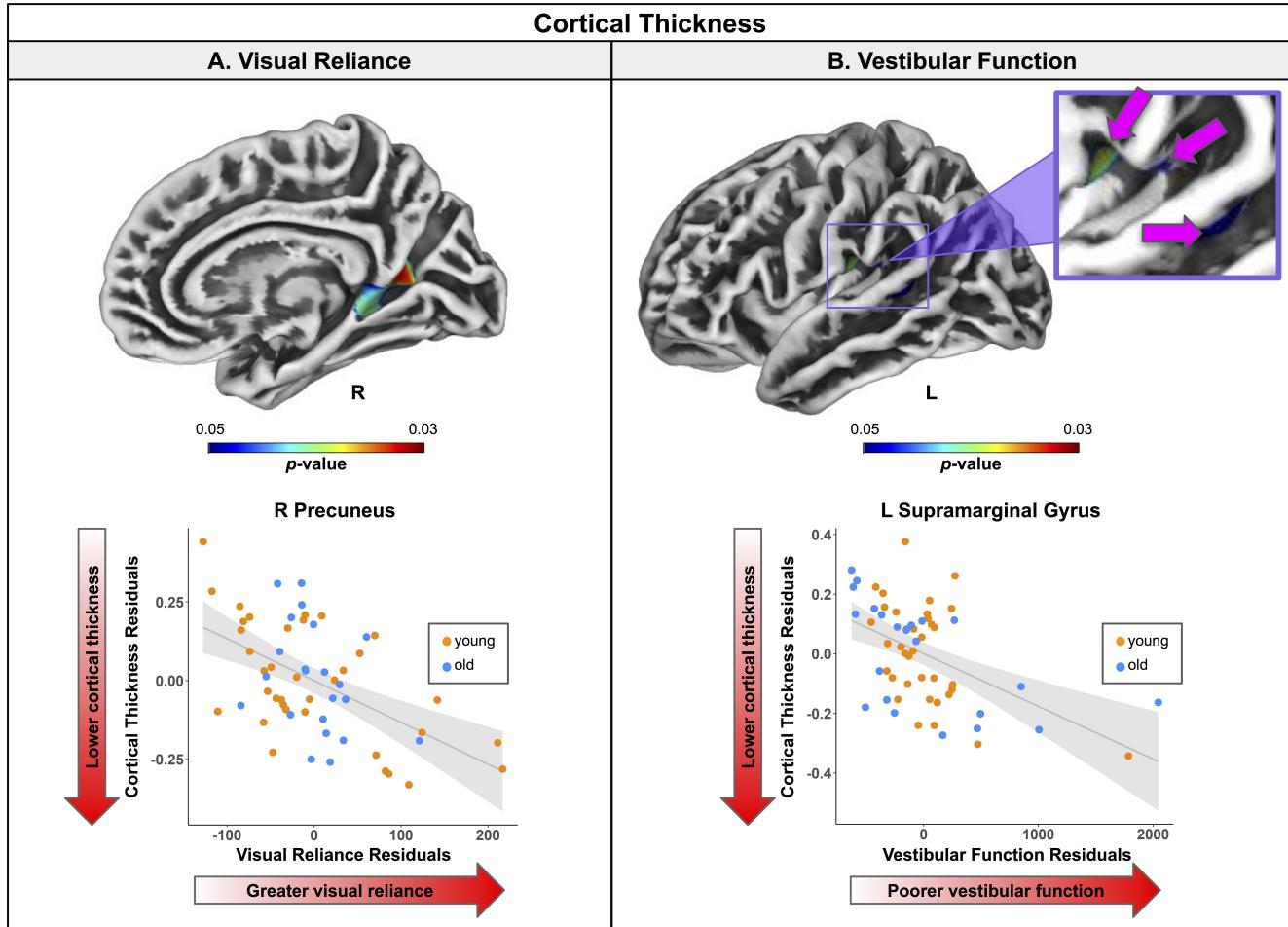


Figure 3: Regions of correlation between cortical thickness and balance scores. Top. Regions showing statistically significant ($p_{FWE-corr} < 0.05$) relationships between cortical thickness and vision (left) and vestibular (right) balance scores. Warmer colors indicate regions of stronger correlation. Results are overlaid onto CAT12 standard space templates. L = left hemisphere; R = right hemisphere. Bottom. Surface values for the peak result coordinate for each model are plotted against balance scores to illustrate examples of the relationships identified by the voxelwise statistical tests. The fit line and confidence interval shading are included only to aid visualization of these relationships. We plotted the residuals instead of the raw values here to adjust for the effects of the age and sex covariates included in each model.

396 temporal, and parietal cortices was associated with poorer vestibular function scores (Fig. 4;
 397 Table 4). That is, those individuals who had the highest gyrification index in these regions also
 398 exhibited the most postural sway during the ECF relative to the EO condition (indicating poorer
 399 vestibular function). This relationship between "better" brain structure and worse vestibular
 400 function is seemingly contradictory, though these resulting regions did *not* include the so-called
 401 vestibular cortices (Lopez et al., 2012; zu Eulenburg et al., 2012). It could be that those with
 402 poorer vestibular function rely more on other brain regions for balance, as compensation. We
 403 expand on this idea in the Discussion.

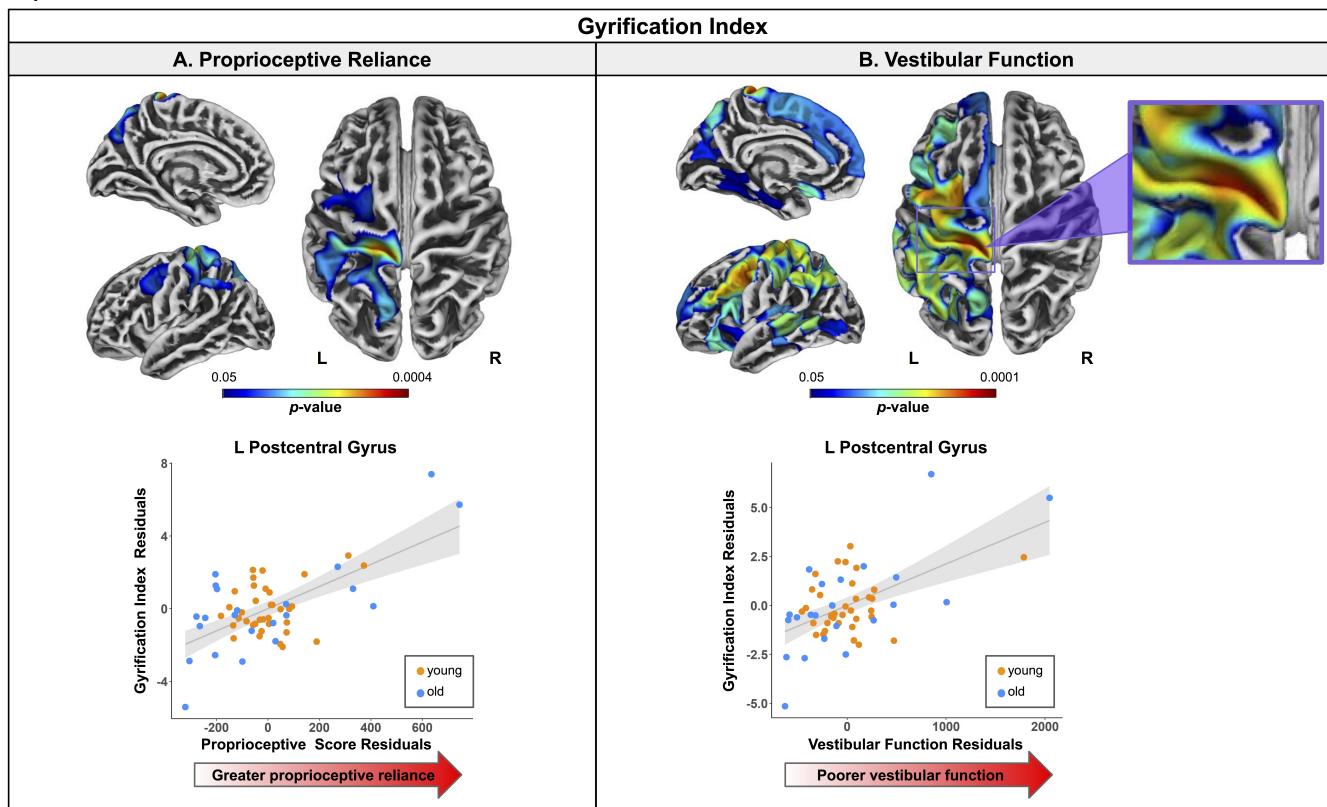


Figure 4: Regions of correlation between gyrification index and balance scores. Top. Regions showing statistically significant ($p_{FWE-corr} < 0.05$) relationships between gyrification index and proprioceptive (A) and vestibular (B) balance scores. Warmer colors indicate regions of stronger correlation. Results are overlaid onto CAT12 standard space templates. L = left hemisphere; R = right hemisphere. Bottom. Surface values for the peak result coordinate for each model are plotted against balance score to illustrate examples of the relationships identified by the voxelwise statistical tests. The fit line and confidence interval shading are included only to aid visualization of these relationships. We plotted the residuals instead of the raw values here to adjust for the effects of the age and sex covariates included in each model.

Table 4: Regions of correlation between gyration index and balance scores

Region	Overlap of Atlas Region	Extent (k_E)	TFCE Level $p_{FWE-corr}$
Proprioceptive reliance			
L postcentral gyrus	30%	2555	<0.001***
L superior parietal cortex	29%	—	—
L supramarginal gyrus	19%	—	—
L precentral gyrus	14%	—	—
L precuneus	5%	—	—
L inferior parietal cortex	2%	—	—
L paracentral gyrus	1%	—	—
L caudal middle frontal gyrus	54%	800	0.02*
L precentral gyrus	32%	—	—
L superior frontal gyrus	14%	—	—
Vestibular function			
L superior frontal gyrus	12%	13292	<0.001***
L superior parietal cortex	11%	—	—
L precentral gyrus	9%	—	—
L postcentral gyrus	9%	—	—
L supramarginal gyrus	7%	—	—
L inferior parietal cortex	6%	—	—
L rostral middle frontal gyrus	6%	—	—
L caudal middle frontal gyrus	5%	—	—
L insula	4%	—	—
L lateral orbitofrontal cortex	4%	—	—
L superior temporal cortex	4%	—	—
L superior temporal sulcus (bank)	3%	—	—
L pars opercularis	3%	—	—
L middle temporal gyrus	3%	—	—
L precuneus	2%	—	—
L pars triangularis	2%	—	—
L cuneus	2%	—	—
L lateral occipital cortex	2%	—	—
L lateral paracentral gyrus	1%	—	—
L caudal anterior cingulate gyrus	1%	—	—
L medial orbitofrontal gyrus	1%	—	—
L lingual gyrus	32%	961	0.031*
L fusiform gyrus	30%	—	—
L parahippocampal gyrus	28%	—	—
L entorhinal cortex	7%	—	—
L cingulate gyrus (isthmus)	3%	—	—
R lateral orbitofrontal cortex	100%	38	0.049*

Note: Here we list all atlas regions from the Desikan-Killiany DK40 atlas (Desikan et al., 2006) that overlapped with each resulting cluster. We do not list volumetric (e.g., MNI space) coordinates in this table because volumetric coordinates cannot be mapped directly onto cortical surfaces. L = left; R = right. * $p_{FWE-corr} < 0.05$; ** $p_{FWE-corr} < 0.001$. Significant p values are bolded.

404 Poorer vestibular function scores were also associated with lower ADt (i.e., typically inter-
405 preted as "worse" brain structure; Bennett et al., 2010; Madden et al., 2012; Pierpaoli et al.,
406 2001; Song et al., 2003) within the bilateral corpus callosum (portions of the genu, body, and
407 splenium) and right corona radiata, which encompassed portions of the forceps minor, cingu-
408 lum, and corticospinal tracts and the fronto-occipital fasciculus and anterior thalamic radiations
409 (Fig. 5; Table 5). That is, those individuals who exhibited the most postural sway during the
410 ECF relative to EO condition (i.e., poorer vestibular function) had the lowest ADt within these
411 regions noted above.

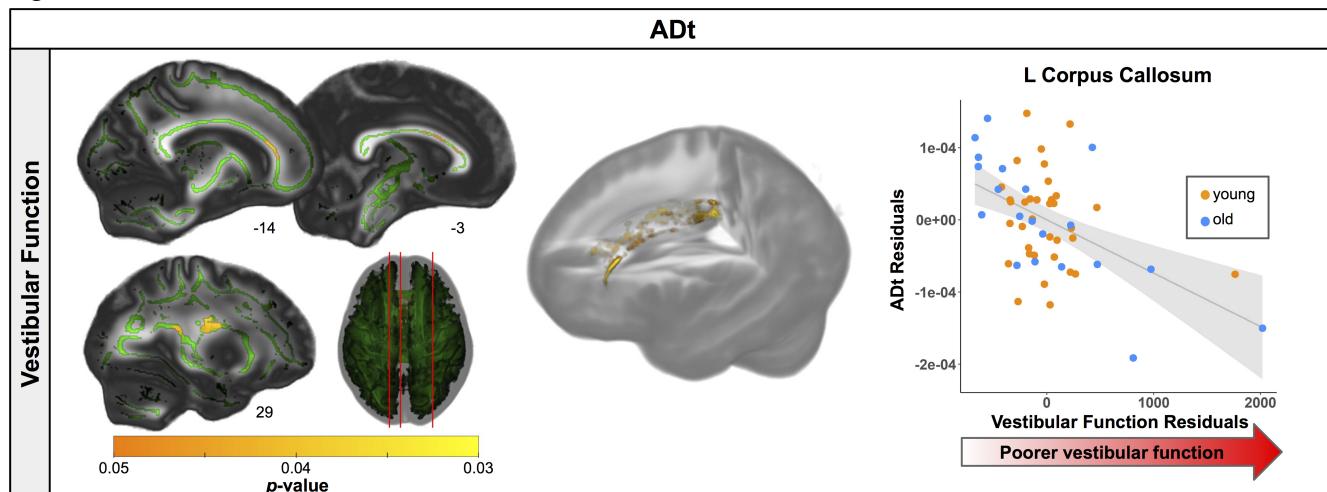


Figure 5: Regions of correlation between ADt and vestibular function scores. Left. Regions showing statistically significant ($p_{FWE-corr} < 0.05$) relationships between ADt and vestibular function scores. Warmer colors indicate regions of stronger correlation. Results are shown on the FMRIB58 FA template with the group mean white matter skeleton (green) overlaid. Right. ADt values for the peak result coordinate are plotted against vestibular function score to illustrate an example of the relationship identified by the voxelwise statistical test. The fit line and confidence interval shading are included only to aid visualization of this relationship. We plotted the residuals instead of the raw values here to adjust for the effects of the age and sex covariates included in each model.

412 **Multiple Regression to Fit the Best Model of Vestibular Function Scores**

413 We used a stepwise multivariate linear regression to compare the predictive strength of the
414 neural correlates of vestibular function score identified above. We entered each participant's
415 vestibular function score as the outcome variable, and their left supramarginal gyrus cortical
416 thickness, left postcentral gyrus gyrification index, and left corpus callosum ADt, as well as age
417 and sex as predictors. The stepwise regression returned a model containing all of these pre-
418 dictors except for sex. That is, the combination of these brain metrics and age (rather than any
419 given metric on its own) best predicted the vestibular function scores (i.e., produced the model

Table 5: Regions of correlation between ADt and balance scores

Region	Extent (k_E)	TFCE Level	MNI Coordinates (mm)		
		$p_{FWE-corr}$	X	Y	Z
L corpus callosum (genu) / L forceps minor, L cingulum	630	0.033*	-12	27	15
L corpus callosum (genu) / L forceps minor, L cingulum	–	0.039*	-13	33	6
R corpus callosum (body) / superior long. fasciculus	–	0.042*	5	14	21
R corpus callosum (splenium)	607	0.035*	12	-36	-24
R superior corona radiata / R corticospinal tract	–	0.037*	29	-13	24
R posterior corona radiata / R anterior thalamic radiation, R inferior fronto-occipital fasciculus	–	0.039*	27	-33	22
L corpus callosum (body)	18	0.048*	-7	-8	28
R corpus callosum (body)	40	0.048*	7	-19	26
R corpus callosum (body)	11	0.049*	12	12	26

Note: Here we list up to three local maxima separated by more than 8 mm per cluster for all clusters with size $k > 10$ voxels. The clusters were labeled using two atlases: the Johns Hopkins University (JHU) ICBM-DTI-82 White Matter Labels (listed first, to the left side of the slash), and the JHU White Matter Tractography atlas within FSL (listed second, to the right side of the slash) (Hua et al., 2008; Wakana et al., 2007). The clusters were sorted by $p_{FWE-corr}$ value (from smallest to largest), then by cluster size (from largest to smallest). L = left. * $p_{FWE-corr} < 0.05$. Significant p values are bolded.

420 with the smallest AIC; Table 6).

421 Table 6: Stepwise multiple regression results for the best model of vestibular balance scores

Predictors	Estimates (SE)	t	p	R^2
Intercept	4538.72 (1765.89)	2.57	0.013*	
L supramarginal gyrus cortical thickness	-1192.86 (280.88)	-4.25	<0.001***	
L postcentral gyrus gyration index	82.09 (28.25)	2.91	0.005**	
L corpus callosum (genu) ADt	-2191567.80 (719575.72)	-3.05	0.004**	
Age	6.12 (2.02)	3.03	0.004**	
				0.61

Note: Here we report the results of the stepwise multiple linear regression testing for the best model of vestibular balance scores. As diffusion-weighted results were included in this model, $n = 35$ young and 20 older adults. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Significant p values are bolded.

422 **Discussion**

423 We identified age group differences for two of the three balance scores, i.e., higher pro-
424 prioreceptive reliance and poorer vestibular function scores for older adults. This indicates that,
425 compared with young adults, older adults rely more heavily on proprioceptive inputs for main-
426 taining balance, and have poorer vestibular function. We also observed multiple significant

427 relationships between brain structure and balance scores. Thinner cortex (i.e., "worse" brain
428 structure) in regions related to multisensory integration correlated with greater reliance on vi-
429 sual inputs for balance. Higher gyrification index (i.e., more "youth-like" brain structure) within
430 the sensorimotor and parietal cortices correlated with greater reliance on proprioceptive inputs
431 for balance. Thinner cortex in regions related to vestibular function and lower ADt (i.e., "worse"
432 brain structure) in the superior-posterior corona radiata and across the corpus callosum were
433 correlated with poorer vestibular function. Higher gyrification index (i.e., more "youth-like" brain
434 structure) in the sensorimotor, parietal, and frontal cortices was also correlated with poorer
435 vestibular function. These results provide greater understanding of the structural correlates of
436 standing balance control and highlight potential targets for future interventions.

437 ***Age Differences in Balance Scores***

438 Older adults exhibited comparatively more difficulty standing on a foam compared to a firm
439 surface (i.e., higher proprioceptive reliance scores) and during the ECF versus EO condition
440 (i.e., poorer vestibular function scores). There were no age group differences in vision scores.
441 Visual reliance scores (sometimes referred to as a Romberg Quotient) are usually higher for
442 older compared with young adults (e.g., Doyle et al., 2004), though at least one study has re-
443 ported a lack of age differences in the Romberg Quotient (Lê and Kapoula, 2008). Similar to our
444 results, previous work has identified the greatest postural sway for older compared with young
445 adults when a compliant (e.g., foam) surface is introduced (e.g., Choy et al., 2003; Woollacott
446 et al., 1986). Thus, compared with the young adults, the older adults here may have relied
447 similarly on visual inputs but more so on proprioceptive information for controlling their balance.

448 Though here we interpret higher visual and proprioceptive scores as indicative of greater
449 reliance on these systems for balance, the interpretation of these scores may be more compli-
450 cated. These scores might index sensory reweighting and integration more so than "reliance" on
451 one sensory system. For example, an increase in postural sway between the EO and EC con-
452 ditions cannot be attributed only to reliance on visual inputs for balance. It could also indicate
453 difficulty upweighting and properly integrating afferent proprioceptive and vestibular information
454 (Kalron, 2017). Aging has a negative impact on sensory reweighting and integration processes

455 (Colledge et al., 1994; Stelmach et al., 1989; Teasdale et al., 1991; Woollacott et al., 1986). For
456 example, when visual or proprioceptive inputs are removed or altered and then reintroduced,
457 young adults can adapt rapidly and reduce their postural sway, whereas older adults exhibit
458 more postural sway and less adaptation when a new or additional sensory channel is initially
459 added (Hay et al., 1996; Teasdale et al., 1991). Thus, the higher proprioceptive reliance and
460 poorer vestibular function scores we observed for older adults might be due in part to greater
461 difficulty with sensory integration.

462 ***Brain Structure Correlates of Visual Reliance Scores***

463 Across both age groups, thinner cortex within the right cingulate gyrus, precuneus, and lin-
464 gual gyrus was associated with higher visual reliance scores. Those who exhibited the greatest
465 increase in postural sway between conditions with the eyes closed versus open had the thinnest
466 cortex in these regions. These brain regions do not relate specifically to visual function, but in-
467 stead play a role in multisensory processing including attentional control, internally-directed
468 cognition, and task engagement (posterior cingulate cortex; Pearson et al., 2011), integration
469 of information and perception of the environment (precuneus; Cavanna and Trimble, 2006), and
470 spatial memory (right lingual gyrus; Sulpizio et al., 2013). It could be that greater reliance on
471 visual inputs is due in part to poorer proprioceptive and vestibular function, and / or brain struc-
472 ture subserving the proprioceptive and vestibular systems (e.g., poorer brain structure in these
473 multisensory processing areas). Thus, individuals may downweight these two systems and rely
474 more on the visual system for balance when all three sensory inputs are available.

475 This finding could also have been related to sensory integration processes more gener-
476 ally. Poorer brain structure in these multisensory integration regions could have contributed to
477 slower, less effective integration of proprioceptive and vestibular inputs to maintain balance in
478 the absence of visual cues. This would then result in more sway when vision was removed
479 (i.e., higher visual reliance scores). It should be noted that we anticipated better structure (i.e.,
480 thicker cortex) in visual processing regions for individuals who typically rely more on vision for
481 balance, due to experience-dependent plasticity processes (May, 2011); however, we did not
482 identify any relationships between canonical visual processing areas and visual reliance scores.

483 ***Brain Structure Correlates of Proprioceptive Reliance Scores***

484 Higher gyrification indices within portions of the left sensorimotor, parietal, supramarginal,
485 paracentral, frontal cortices and precuneus were associated with higher proprioceptive scores
486 (i.e., more difficulty on foam versus firm). Interestingly, the sensorimotor cortex cluster (where
487 the strongest brain-behavior relationship occurred) was located in the cortical region specif-
488 ically related to lower limb sensorimotor function. Gyrification index generally declines with
489 aging (Cao et al., 2017; Hogstrom et al., 2013; Lamballais et al., 2020; Madan, 2021; Madan
490 and Kensinger, 2018); lower gyrification indices may indicate poorer regional brain structure,
491 i.e., less cortex buried within the sulcal folds (Luders et al., 2006). Thus, it follows that lower
492 gyrification index in a region specifically related to processing lower limb somatosensory in-
493 formation would be associated with less reliance on proprioceptive inputs for balance. As de-
494 scribed above, it could be that poorer structure in the brain regions primarily associated with
495 processing one type of sensory information (e.g., proprioceptive) correlates with less reliance
496 on that system and more reliance on other systems (e.g., visual) for maintaining balance.

497 ***Brain Structure Correlates of Vestibular Function Scores***

498 Thinner cortex within two regions encompassing portions of the left supramarginal and post-
499 central gyri and the bank of the left superior temporal sulcus was associated with poorer vestibu-
500 lar function scores. Stated differently, those individuals who exhibited comparatively more pos-
501 tural sway during the ECF compared to the EO condition also had the thinnest cortex in these
502 regions. These brain regions contribute to vestibular processing and are consistent with vestibu-
503 lar networks identified by our prior functional MRI work (Hupfeld et al., 2020, 2021b; Noohi et al.,
504 2017, 2019) as well as meta-analyses identifying vestibular cortex (Lopez et al., 2012; zu Eu-
505 lenburg et al., 2012). The supramarginal gyrus is also thought to contribute to proprioception
506 (Ben-Shabat et al., 2015), whole body spatial orientation (Fiori et al., 2015; Kheradmand et al.,
507 2015), and integration of vestibular inputs with visual and proprioceptive information (Ionta et al.,
508 2011). This portion of the temporal sulcus contributes to sensory integration (particularly of au-
509 diovisual inputs; Hein and Knight, 2008; Vander Wyk et al., 2009). Thus, it is logical that those
510 with the poorest brain structure (i.e., the thinnest cortex) in these brain regions specifically re-

511 lated to vestibular and multisensory processing also encounter the most difficulty standing with
512 minimal postural sway during a balance condition that specifically tasks the vestibular system.

513 Higher gyrification indices within parts of the left sensorimotor, parietal, supramarginal, para-
514 central, frontal cortices and precuneus were associated with poorer vestibular function scores
515 (i.e., more difficulty during ECF compared to EO). This relationship between higher gyrification
516 index and poorer vestibular function is seemingly contradictory. However, as opposed to the
517 relationship described above between thinner vestibular cortex and poorer vestibular function,
518 resulting brain regions for this relationship did not include the vestibular cortices (Lopez et al.,
519 2012; zu Eulenburg et al., 2012). Instead, the strongest relationship between higher gyrification
520 index (i.e., more "youth-like" brain structure) and poorer vestibular function occurred in the me-
521 dial pre- and postcentral gyri, which are related to axial and lower limb sensorimotor processing.
522 It could be that those with poorer vestibular function rely more heavily on other brain regions
523 and sensory systems for balance as a compensatory mechanism. However, it should also be
524 noted that the interpretation of gyrification index may be more complex, as a recent study identi-
525 fied relationships between better cognitive function and both higher and lower gyrification index
526 in normal aging and Parkinson's disease (Chaudhary et al., 2020).

527 Poorer vestibular function scores were associated with lower ADt within the bilateral corpus
528 callosum and right corona radiata, which encompassed portions of the forceps minor, cingu-
529 lum, and corticospinal tracts and the fronto-occipital fasciculus and anterior thalamic radiations.
530 Those who exhibited the greatest increases in postural sway between the ECF and EO condi-
531 tions also had the lowest ADt in these regions. Lower ADt is hypothesized to indicate accumula-
532 tion of debris or metabolic damage (Madden et al., 2012), axonal injury and subsequent gliosis
533 (Pierpaoli et al., 2001; Song et al., 2003), or disrupted macrostructural organization (Bennett
534 et al., 2010). Across the brain, ADt was largely lower for the older compared with young adults
535 in this dataset (Hupfeld et al., 2021a). Thus, it is logical that lower ADt in these white mat-
536 ter tracts related to interhemispheric communication and motor function would relate to poorer
537 vestibular function.

538 **Lack of Age Differences in Brain-Behavior Relationships**

539 It is somewhat surprising that we did not identify age differences in the relationship between
540 brain structure and balance. One previous study reported relationships between brain structure
541 and balance for older but not younger adults (Van Impe et al., 2012). In our prior work on
542 this dataset (Hupfeld et al., 2021a), we identified multiple relationships between brain structure
543 and dual task walking for older but not young adults. It is worth noting that this is a group of
544 high functioning older adults in relatively good health, thus, the balance tasks used here may not
545 have been sufficiently biomechanically challenging or cognitively-demanding for age differences
546 in brain-behavior relationships to emerge. If we had incorporated a secondary cognitive task,
547 perhaps we would have found age group differences. Performing a secondary cognitive task has
548 been found to disproportionately affect older adults (e.g., increasing sway variability by 5% for
549 young adults but 37% for older adults; Maylor et al., 2001). An executive function secondary task
550 would have required greater contributions from the prefrontal cortex. Given the large body of
551 literature reporting age-related differences in frontal cortex structure (Fjell et al., 2009; Lemaitre
552 et al., 2012; Salat et al., 2004; Thambisetty et al., 2010), and that balance may require greater
553 attentional control in older age (Dault et al., 2001a,b; Doumas et al., 2009; Huxhold et al., 2006;
554 Rankin et al., 2000), a task with a more challenging cognitive component may have resulted in
555 a correlation between prefrontal cortex structure and balance for the older but not the younger
556 adults.

557 **Limitations**

558 By using a cross-sectional approach, we could not track concurrent changes in brain struc-
559 ture and balance over time. This approach prevented us from testing whether increased reliance
560 on vision and proprioception over time – in compensation for longitudinal declines in vestibular
561 function – could result in neuroplastic changes in the brain regions responsible for processing
562 these inputs. In addition, the vestibular score did not fully isolate vestibular from proprioceptive
563 contributions; as we compared a foam condition (ECF) to EO, the vestibular score incorporated
564 both proprioceptive and vestibular challenges. Future work could probe additional balance con-
565 ditions such as a full NeuroCom Sensory Organization Test (SOT), which includes visual conflict

566 conditions. We did not examine other balance outcome variables, such as sway range or velocity.
567 Lastly, in the current acquisition protocol we had a single-shell diffusion sequence. Future
568 studies should consider a multi-shell sequence for a more robust estimation of the free water
569 fraction.

570 ***Conclusions and Future Directions***

571 We identified relationships between regional brain structure (cortical thickness, gyration
572 index, and ADt) and balance scores indicative of reliance on visual and proprioceptive inputs
573 and vestibular function. Understanding which brain regions contribute to different aspects of
574 balance could be useful in developing future interventions. tDCS, a form of noninvasive brain
575 stimulation, has been demonstrated to augment balance performance and training for both
576 young and older adults (Hupfeld et al., 2017a,b; Kaminski et al., 2016; Yosephi et al., 2018).
577 Uncovering how brain structure relates to balance function could help identify regions to target
578 with tDCS. This is a promising future intervention, with some evidence showing that tDCS
579 affects brain function (Pupíková et al., 2021) and neurochemicals (Heimrath et al., 2020), and
580 produces effects that may last for months post-stimulation (Vestito et al., 2014).

581 **Conflict of Interest**

582 The authors declare that the research was conducted in the absence of any commercial or
583 financial relationships that could be construed as a potential conflict of interest.

584 **Author Contributions**

585 KH led the initial study design, collected and preprocessed all of the neuroimaging and gait
586 data, conducted all statistical analyses, created the figures and tables, and wrote the first draft
587 of the manuscript. OP and HR consulted on DWI preprocessing and contributed to manuscript
588 preparation. CH consulted on the design and analysis of the gait assessments. RS oversaw
589 project design and led the interpretation and discussion of the results. All authors participated
590 in revision of the manuscript.

591 **Funding**

592 During completion of this work, KH was supported by a National Science Foundation Grad-
593 uate Research Fellowship under Grant no. DGE-1315138 and DGE-1842473, National Insti-
594 tute of Neurological Disorders and Stroke training grant T32-NS082128, and National Institute
595 on Aging fellowship 1F99AG068440. HM was supported by a Natural Sciences and Engi-
596 neering Research Council of Canada postdoctoral fellowship and a NASA Human Research
597 Program augmentation grant. RS was supported by a grant from the National Institute on Ag-
598 ing U01AG061389. A portion of this work was performed in the McKnight Brain Institute at
599 the National High Magnetic Field Laboratory's Advanced Magnetic Resonance Imaging and
600 Spectroscopy (AMRIS) Facility, which is supported by National Science Foundation Cooper-
601 ative Agreement No. DMR-1644779 and the State of Florida.

602 **Acknowledgments**

603 The authors wish to thank Aakash Anandjiwala, Justin Geraghty, Pilar Alvarez Jerez, and
604 Alexis Jennings-Coulibaly for their assistance in subject recruitment and data collection, as well
605 as Sutton Richmond for his help in applying the signal drift correction to the diffusion-weighted

606 data. The authors also wish to thank all of the participants who volunteered their time, as well
607 as the McKnight Brain Institute MRI technologists, without whom this project would not have
608 been possible.

609 **References**

610 Abrahamova, D., Hlavačka, F., 2008. Age-related changes of human balance during quiet
611 stance. *Physiol. Res.* 57, 957–964.

612 Ackermann, H., Scholz, E., Koehler, W., Dichgans, J., 1991. Influence of posture and volun-
613 tary background contraction upon compound muscle action potentials from anterior tibial and
614 soleus muscle following transcranial magnetic stimulation. *Electroencephalogr. Clin. Neuro-
615 physiol.* 81, 71–80. doi:10.1016/0168-5597(91)90106-8.

616 Alhanti, B., Bruder, L.A., Creese, W., Golden, R.L., Gregory, C., Newton, R.A., 1997. Bal-
617 ance abilities of community dwelling older adults under altered visual and support surface
618 conditions. *Phys. Occup. Ther. Geriatr.* 15, 37–52. doi:10.1080/J148v15n01_03.

619 Andersson, J.L., Jenkinson, M., Smith, S., Andersson, J., 2007a. Non-linear optimisation.
620 FMRIB technical report tr07ja1. FMRIB Analysis Group of the University of Oxford .

621 Andersson, J.L., Jenkinson, M., Smith, S., et al., 2007b. Non-linear registration, aka spatial
622 normalisation FMRIB technical report tr07ja2. FMRIB Analysis Group of the University of
623 Oxford .

624 Andersson, J.L., Skare, S., Ashburner, J., 2003. How to correct susceptibility distortions in spin-
625 echo echo-planar images: application to diffusion tensor imaging. *NeuroImage* 20, 870–888.
626 doi:10.1016/S1053-8119(03)00336-7.

627 Andersson, J.L., Sotiropoulos, S.N., 2016. An integrated approach to correction for off-
628 resonance effects and subject movement in diffusion MR imaging. *NeuroImage* 125, 1063–
629 1078. doi:10.1016/j.neuroimage.2015.10.019.

630 Ashburner, J., Barnes, G., Chen, C.C., Daunizeau, J., Flandin, G., Friston, K., Kiebel, S., Kilner,
631 J., Litvak, V., Moran, R., et al., 2014. SPM12 manual. Wellcome Trust Centre for Neuroimag-
632 ing, London, UK 2464.

633 Avants, B.B., Tustison, N.J., Song, G., Cook, P.A., Klein, A., Gee, J.C., 2011. A reproducible
634 evaluation of ANTs similarity metric performance in brain image registration. *NeuroImage* 54,
635 2033–2044. doi:10.1016/j.neuroimage.2010.09.025.

636 Avants, B.B., Yushkevich, P., Pluta, J., Minkoff, D., Korczykowski, M., Detre, J., Gee, J.C., 2010.
637 The optimal template effect in hippocampus studies of diseased populations. *NeuroImage*
638 49, 2457–2466. doi:10.1016/j.neuroimage.2009.09.062.

639 Baudry, S., Duchateau, J., 2012. Age-related influence of vision and proprioception on ia
640 presynaptic inhibition in soleus muscle during upright stance. *J. Physiol* 590, 5541–5554.
641 doi:10.1113/jphysiol.2012.228932.

642 Ben-Shabat, E., Matyas, T.A., Pell, G.S., Brodtmann, A., Carey, L.M., 2015. The right supra-
643 marginal gyrus is important for proprioception in healthy and stroke-affected participants: a
644 functional MRI study. *Front. Neurol.* 6, 248. doi:10.3389/fneur.2015.00248.

645 Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful
646 approach to multiple testing. *J. R. Stat. Soc. Series B Stat. Methodol.* 57, 289–300. doi:10.
647 1111/j.2517-6161.1995.tb02031.x.

648 Bennett, I.J., Madden, D.J., Vaidya, C.J., Howard, D.V., Howard, J.H., 2010. Age-related dif-
649 ferences in multiple measures of white matter integrity: A diffusion tensor imaging study of
650 healthy aging. *Hum. Brain Mapp.* 31. doi:10.1002/hbm.20872.

651 Boelens, C., Hekman, E.E., Verkerke, G.J., 2013. Risk factors for falls of older citizens. *Technol.*
652 *Health Care* 21, 521–533. doi:10.3233/THC-130748.

653 Boisgontier, M.P., Cheval, B., Chalavi, S., van Ruitenbeek, P., Leunissen, I., Levin, O., Nieuw-
654 boer, A., Swinnen, S.P., 2017. Individual differences in brainstem and basal ganglia structure
655 predict postural control and balance loss in young and older adults. *Neurobiol. Aging* 50,
656 47–59. doi:10.1016/j.neurobiolaging.2016.10.024.

657 Cao, B., Mwangi, B., Passos, I.C., Wu, M.J., Keser, Z., Zunta-Soares, G.B., Xu, D., Hasan, K.M.,
658 Soares, J.C., 2017. Lifespan gyration trajectories of human brain in healthy individuals and

659 patients with major psychiatric disorders. *Sci. Rep.* 7, 1–8. doi:10.1038/s41598-017-00582-
660 1.

661 Carson, N., Leach, L., Murphy, K.J., 2018. A re-examination of montreal cognitive assessment
662 (MoCA) cutoff scores. *Int. J. Geriatr. Psychiatry* 33, 379–388. doi:10.1002/gps.4756.

663 Cavanna, A.E., Trimble, M.R., 2006. The precuneus: a review of its functional anatomy and
664 behavioural correlates. *Brain* 129, 564–583. doi:10.1093/brain/awl004.

665 Cham, R., Perera, S., Studenski, S.A., Bohnen, N.I., 2007. Striatal dopamine denervation and
666 sensory integration for balance in middle-aged and older adults. *Gait Posture* 26, 516–525.
667 doi:10.1016/j.gaitpost.2006.11.204.

668 Chaudhary, S., Kumaran, S.S., Goyal, V., Kaloiya, G., Kalaivani, M., Jagannathan, N., Sagar, R.,
669 Mehta, N., Srivastava, A., 2020. Cortical thickness and gyrification index measuring cognition
670 in Parkinson's disease. *Int. J. Neurosci.* , 1–10doi:10.1080/00207454.2020.1766459.

671 Choy, N.L., Brauer, S., Nitz, J., 2003. Changes in postural stability in women aged 20 to 80
672 years. *J. Gerontol. A Biol. Sci. Med. Sci.* 58, M525–M530. doi:10.1093/gerona/58.6.M525.

673 Cohen, H., Blatchly, C.A., Gombash, L.L., 1993. A study of the clinical test of sensory interaction
674 and balance. *Phys. Ther.* 73, 346–351. doi:10.1093/ptj/73.6.346.

675 Colledge, N., Cantley, P., Peaston, I., Brash, H., Lewis, S., Wilson, J., 1994. Ageing and
676 balance: the measurement of spontaneous sway by posturography. *Gerontology* 40, 273–
677 278. doi:10.1159/000213596.

678 Dahnke, R., Yotter, R.A., Gaser, C., 2013. Cortical thickness and central surface estimation.
679 *NeuroImage* 65, 336–348. doi:10.1016/j.neuroimage.2012.09.050.

680 Dault, M.C., Frank, J.S., Allard, F., 2001a. Influence of a visuo-spatial, verbal and central
681 executive working memory task on postural control. *Gait Posture* 14, 110–116. doi:10.1016/
682 S0966-6362(01)00113-8.

683 Dault, M.C., Geurts, A.C., Mulder, T.W., Duysens, J., 2001b. Postural control and cognitive task
684 performance in healthy participants while balancing on different support-surface configura-
685 tions. *Gait Posture* 14, 248–255. doi:10.1016/S0966-6362(01)00130-8.

686 Dawson, N., Dzurino, D., Karleskint, M., Tucker, J., 2018. Examining the reliability, correlation,
687 and validity of commonly used assessment tools to measure balance. *Health Sci. Rep.* 1,
688 e98. doi:10.1002/hsr2.98.

689 Desikan, R.S., Ségonne, F., Fischl, B., Quinn, B.T., Dickerson, B.C., Blacker, D., Buckner, R.L.,
690 Dale, A.M., Maguire, R.P., Hyman, B.T., et al., 2006. An automated labeling system for
691 subdividing the human cerebral cortex on MRI scans into gyral based regions of interest.
692 *NeuroImage* 31, 968–980. doi:10.1016/j.neuroimage.2006.01.021.

693 Dewey, R.S., Gomez, R., Degg, C., Baguley, D.M., Glover, P., 2020. Qualitative and quantitative
694 assessment of magnetic vestibular stimulation in humans. *J. Vestib. Res.* , 1–9.

695 Diedrichsen, J., 2006. A spatially unbiased atlas template of the human cerebellum. *NeuroIm-
696 age* 33, 127–138. doi:10.1016/j.neuroimage.2006.05.056.

697 Diedrichsen, J., Balsters, J.H., Flavell, J., Cussans, E., Ramnani, N., 2009. A probabilistic MR
698 atlas of the human cerebellum. *NeuroImage* 46, 39–46. doi:10.1016/j.neuroimage.2009.
699 01.045.

700 Dillon, C.F., 2010. Vision, hearing, balance, and sensory impairment in Americans aged 70
701 years and over: United States, 1999-2006. 31, US Department of Health and Human Ser-
702 vices, Centers for Disease Control and Prevention.

703 Doumas, M., Rapp, M.A., Krampe, R.T., 2009. Working memory and postural control: adult
704 age differences in potential for improvement, task priority, and dual tasking. *J. Gerontol. B
705 Psychol. Sci. Soc. Sci.* 64, 193–201. doi:10.1093/geronb/gbp009.

706 Doyle, T.L., Dugan, E.L., Humphries, B., Newton, R.U., 2004. Discriminating between elderly
707 and young using a fractal dimension analysis of centre of pressure. *Int. J. Med. Sci.* 1, 11.
708 doi:10.7150/ijms.1.11. Available from.

709 Elias, L.J., Bryden, M.P., Bulman-Fleming, M.B., 1998. Footedness is a better predictor than is
710 handedness of emotional lateralization. *Neuropsychologia* 36, 37–43. doi:10.1016/S0028-
711 3932(97)00107-3.

712 zu Eulenburg, P., Caspers, S., Roski, C., Eickhoff, S.B., 2012. Meta-analytical definition and
713 functional connectivity of the human vestibular cortex. *NeuroImage* 60, 162–169. doi:10.
714 1016/j.neuroimage.2011.12.032.

715 Field, A., Miles, J., Field, Z., 2012. *Discovering Statistics Using R*. Sage Publications.

716 Fiori, F., Candidi, M., Acciarino, A., David, N., Aglioti, S.M., 2015. The right temporoparietal
717 junction plays a causal role in maintaining the internal representation of verticality. *J. Neuro-
718 physiol.* 114, 2983–2990. doi:10.1152/jn.00289.2015.

719 Fjell, A.M., Walhovd, K.B., Fennema-Notestine, C., McEvoy, L.K., Hagler, D.J., Holland, D.,
720 Brewer, J.B., Dale, A.M., 2009. One-year brain atrophy evident in healthy aging. *J. Neurosci.*
721 29, 15223–15231. doi:10.1523/JNEUROSCI.3252-09.2009.

722 Gaser, C., Dahnke, R., et al., 2016. CAT-a computational anatomy toolbox for the analysis of
723 structural MRI data. *Hum. Brain Mapp.* 2016, 336–348.

724 Gaser, C., Kurth, F., 2017. Manual computational anatomy toolbox-CAT12. Structural Brain
725 Mapping Group at the Departments of Psychiatry and Neurology, University of Jena.

726 Goble, D.J., Brar, H., Brown, E.C., Marks, C.R., Baweja, H.S., 2019. Normative data for the
727 balance tracking system modified clinical test of sensory integration and balance protocol.
728 *Med. Devices* 12, 183.

729 Goble, D.J., Brown, E.C., Marks, C.R., Baweja, H.S., 2020. Expanded normative data for the
730 balance tracking system modified clinical test of sensory integration and balance protocol.
731 *Med. Devices* 3, e10084.

732 Godin, G., Shephard, R., et al., 1985. A simple method to assess exercise behavior in the
733 community. *Can. J. Appl. Sport Sci.* 10, 141–146.

734 Hay, L., Bard, C., Fleury, M., Teasdale, N., 1996. Availability of visual and proprioceptive afferent
735 messages and postural control in elderly adults. *Exp. Brain Res.* 108, 129–139.

736 Heimrath, K., Brechmann, A., Blobel-Lüer, R., Stadler, J., Budinger, E., Zaehle, T., 2020. Tran-
737 scranial direct current stimulation (tDCS) over the auditory cortex modulates GABA and glu-
738 tamate: a 7 T MR-spectroscopy study. *Sci. Rep.* 10, 1–8. doi:10.1038/s41598-020-77111-0.

739 Hein, G., Knight, R.T., 2008. Superior temporal sulcus—it's my area: or is it? *J. Cogn. Neurosci.*
740 20, 2125–2136. doi:10.1162/jocn.2008.20148.

741 Hoddes, E., Zarcone, V., Dement, W., 1972. Stanford sleepiness scale. *Enzyklopädie der*
742 *Schlafmedizin* 1184.

743 Hogstrom, L.J., Westlye, L.T., Walhovd, K.B., Fjell, A.M., 2013. The structure of the cerebral
744 cortex across adult life: age-related patterns of surface area, thickness, and gyration.
745 *Cereb. Cortex* 23, 2521–2530. doi:10.1093/cercor/bhs231.

746 Horak, F.B., 2006. Postural orientation and equilibrium: what do we need to know about neural
747 control of balance to prevent falls? *Age Ageing* 35, ii7–ii11. doi:10.1093/ageing/af1077.

748 Hua, K., Zhang, J., Wakana, S., Jiang, H., Li, X., Reich, D.S., Calabresi, P.A., Pekar, J.J., van
749 Zijl, P.C., Mori, S., 2008. Tract probability maps in stereotaxic spaces: analyses of white
750 matter anatomy and tract-specific quantification. *NeuroImage* 39, 336–347. doi:10.1016/j.
751 *neuroimage*.2007.07.053.

752 Hülsdünker, T., Mierau, A., Neub, C., Kleinöder, H., Strüder, H., 2015. Cortical processes
753 associated with continuous balance control as revealed by EEG spectral power. *Neurosci.*
754 *Lett.* 592, 1–5. doi:10.1016/j.neulet.2015.02.049.

755 Hupfeld, K., Geraghty, J., McGregor, H., Hass, C., Pasternak, O., Seidler, R., 2021a. Differential
756 relationships between brain structure and dual task walking in young and older adults. *bioRxiv*
757 doi:10.1101/2021.11.04.467303.

758 Hupfeld, K., Ketcham, C., Schneider, H., 2017a. Transcranial direct current stimulation (tDCS)
759 to the supplementary motor area (SMA) influences performance on motor tasks. *Exp. Brain*
760 *Res.* 235, 851–859. doi:10.1007/s00221-016-4848-5.

761 Hupfeld, K., McGregor, H., Koppelmans, V., Beltran, N., Kofman, I., De Dios, Y., Riascos,
762 R., Reuter-Lorenz, P., Wood, S., Bloomberg, J., et al., 2021b. Brain and behavioral ev-
763 idence for reweighting of vestibular inputs with long-duration spaceflight. *Cereb. Cortex* ,
764 bhab239doi:10.1093/cercor/bhab239.

765 Hupfeld, K.E., Hyatt, H.W., Alvarez Jerez, P., Mikkelsen, M., Hass, C.J., Edden, R.A., Seidler,
766 R.D., Porges, E.C., 2021c. *In vivo* brain glutathione is higher in older age and correlates with
767 mobility. *Cereb. Cortex* 31, 4576–4594. doi:10.1093/cercor/bhab107.

768 Hupfeld, K.E., Ketcham, C.J., Schneider, H.D., 2017b. Transcranial direct current stimulation
769 (tDCS) to Broca's area: persisting effects on non-verbal motor behaviors. *Neurol. Dis. Ther.*
770 1, 1–5. doi:10.15761/NDT.1000102.

771 Hupfeld, K.E., Lee, J.K., Gadd, N.E., Kofman, I.S., De Dios, Y.E., Bloomberg, J.J., Mulavara,
772 A.P., Seidler, R.D., 2020. Neural correlates of vestibular processing during a spaceflight
773 analog with elevated carbon dioxide (CO₂): a pilot study. *Front. Syst. Neurosci.* 13, 80. doi:10.
774 3389/fnsys.2019.00080.

775 Hupfeld, K.E., Vaillancourt, D.E., Seidler, R.D., 2018. Genetic markers of dopaminergic trans-
776 mission predict performance for older males but not females. *Neurobiol. Aging* 66, 180–e11.
777 doi:10.1016/j.neurobiolaging.2018.02.005.

778 Huxhold, O., Li, S.C., Schmiedek, F., Lindenberger, U., 2006. Dual-tasking postural control:
779 aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Res.*
780 *Bull.* 69, 294–305. doi:10.1016/j.brainresbull.2006.01.002.

781 Ionta, S., Heydrich, L., Lenggenhager, B., Mounthon, M., Fornari, E., Chapuis, D., Gassert, R.,
782 Blanke, O., 2011. Multisensory mechanisms in temporo-parietal cortex support self-location
783 and first-person perspective. *Neuron* 70, 363–374. doi:10.1016/j.neuron.2011.03.009.

784 Jacobs, J., Horak, F., 2007. Cortical control of postural responses. *J. Neural Transm.* 114,
785 1339–1348. doi:10.1007/s00702-007-0657-0.

786 de Jager, C.A., Budge, M.M., Clarke, R., 2003. Utility of TICS-M for the assessment of cognitive
787 function in older adults. *Int. J. Geriatr. Psychiatry* 18, 318–324. doi:10.1002/gps.830.

788 Jenkinson, M., Beckmann, C.F., Behrens, T.E., Woolrich, M.W., Smith, S.M., 2012. FSL. *Neu-
789 roImage* 62, 782–790.

790 Judge, J.O., King, M.B., Whipple, R., Clive, J., Wolf son, L.I., 1995. Dynamic balance in older
791 persons: effects of reduced visual and proprioceptive input. *J. Gerontol. A Biol. Sci. Med. Sci.*
792 50, M263–M270. doi:10.1093/gerona/50A.5.M263.

793 Kalron, A., 2017. The Romberg ratio in people with multiple sclerosis. *Gait Posture* 54, 209–
794 213. doi:10.1016/j.gaitpost.2017.03.016.

795 Kaminski, E., Steele, C.J., Hoff, M., Gundlach, C., Rjosk, V., Sehm, B., Villringer, A., Ragert,
796 P., 2016. Transcranial direct current stimulation (tDCS) over primary motor cortex leg area
797 promotes dynamic balance task performance. *Clin. Neurophysiol. Pract.* 127, 2455–2462.
798 doi:10.1016/j.clinph.2016.03.018.

799 Kheradmand, A., Lasker, A., Zee, D.S., 2015. Transcranial magnetic stimulation (TMS) of the
800 supramarginal gyrus: a window to perception of upright. *Cereb. Cortex* 25, 765–771. doi:10.
801 1093/cercor/bht267.

802 Lamballais, S., Vinke, E.J., Vernooij, M.W., Ikram, M.A., Muetzel, R.L., 2020. Cortical
803 gyration in relation to age and cognition in older adults. *NeuroImage* 212, 116637.
804 doi:10.1016/j.neuroimage.2020.116637.

805 Laughton, C.A., Slavin, M., Katdare, K., Nolan, L., Bean, J.F., Kerrigan, D.C., Phillips, E., Lipsitz,
806 L.A., Collins, J.J., 2003. Aging, muscle activity, and balance control: physiologic changes
807 associated with balance impairment. *Gait Posture* 18, 101–108. doi:10.1016/S0966–
808 6362(02)00200-X.

809 Lê, T.T., Kapoula, Z., 2008. Role of ocular convergence in the romberg quotient. *Gait Posture*
810 27, 493–500. doi:10.1016/j.gaitpost.2007.06.003.

811 Leemans, A., Jeurissen, B., Sijbers, J., Jones, D., 2009. ExploreDTI: a graphical toolbox for
812 processing, analyzing, and visualizing diffusion MR data. *Proc. Int. Soc. Magn. Reson. Med.*
813 *Sci.* 17.

814 Leibowitz, H.W., Shupert, C.L., 1985. Spatial orientation mechanisms and their implications for
815 falls. *Clin. Geriatr. Med.* 1, 571–580. doi:10.1016/S0749-0690(18)30925-X.

816 Lemaitre, H., Goldman, A.L., Sambataro, F., Verchinski, B.A., Meyer-Lindenberg, A., Wein-
817 berger, D.R., Mattay, V.S., 2012. Normal age-related brain morphometric changes: nonuni-
818 formity across cortical thickness, surface area and gray matter volume? *Neurobiol. Aging* 33,
819 617–e1. doi:10.1016/j.neurobiolaging.2010.07.013.

820 Lin, C.C., Barker, J.W., Sparto, P.J., Furman, J.M., Huppert, T.J., 2017. Functional near-infrared
821 spectroscopy (fNIRS) brain imaging of multi-sensory integration during computerized dy-
822 namic posturography in middle-aged and older adults. *Exp. Brain Res.* 235, 1247–1256.
823 doi:10.1007/s00221-017-4893-8.

824 Lopez, C., Blanke, O., Mast, F., 2012. The human vestibular cortex revealed by coordinate-
825 based activation likelihood estimation meta-analysis. *Neuroscience* 212, 159–179. doi:10.
826 1016/j.neuroscience.2012.03.028.

827 Luders, E., Thompson, P.M., Narr, K., Toga, A.W., Jancke, L., Gaser, C., 2006. A curvature-
828 based approach to estimate local gyration on the cortical surface. *NeuroImage* 29, 1224–
829 1230. doi:10.1016/j.neuroimage.2005.08.049.

830 Madan, C.R., 2021. Age-related decrements in cortical gyration: Evidence from an acceler-
831 ated longitudinal dataset. *European J. Neurosci.* 53, 1661–1671. doi:10.1111/ejn.15039.

832 Madan, C.R., Kensinger, E.A., 2018. Predicting age from cortical structure across the lifespan.
833 *European J. Neurosci.* 47, 399–416. doi:10.1111/ejn.13835.

834 Madden, D.J., Bennett, I.J., Burzynska, A., Potter, G.G., Chen, N.k., Song, A.W., 2012. Diffusion
835 tensor imaging of cerebral white matter integrity in cognitive aging. *Biochim. Biophys. Acta*
836 *Mol. Basis Dis.* 1822, 386–400. doi:10.1016/j.bbadi.2011.08.003.

837 Mahboobin, A., Loughlin, P.J., Redfern, M.S., Sparto, P.J., 2005. Sensory re-weighting in human
838 postural control during moving-scene perturbations. *Exp. Brain Res.* 167, 260–267. doi:10.
839 1007/s00221-005-0053-7.

840 Mahoney, J.R., Holtzer, R., Izzetoglu, M., Zemon, V., Verghese, J., Allali, G., 2016. The role of
841 prefrontal cortex during postural control in Parkinsonian syndromes a functional near-infrared
842 spectroscopy study. *Brain Res.* 1633, 126–138.

843 Maki, B.E., Holliday, P.J., Topper, A.K., 1994. A prospective study of postural balance and risk
844 of falling in an ambulatory and independent elderly population. *J. Gerontol.* 49, M72–M84.
845 doi:10.1093/geronj/49.2.M72.

846 Maki, B.E., Perry, S.D., Norrie, R.G., McIlroy, W.E., 1999. Effect of facilitation of sensation
847 from plantar foot-surface boundaries on postural stabilization in young and older adults. *J.*
848 *Gerontol. A Biol. Sci. Med. Sci.* 54, M281–M287. doi:10.1093/gerona/54.6.M281.

849 Mancini, M., Salarian, A., Carlson-Kuhta, P., Zampieri, C., King, L., Chiari, L., Horak, F.B., 2012.
850 iSway: a sensitive, valid and reliable measure of postural control. *J. Neuroeng. Rehabil.* 9,
851 1–8. doi:10.1186/1743-0003-9-59.

852 May, A., 2011. Experience-dependent structural plasticity in the adult human brain. *Trends*
853 *Cogn. Sci.* 15, 475–482. doi:10.1016/j.tics.2011.08.002.

854 Maylor, E.A., Allison, S., Wing, A.M., 2001. Effects of spatial and nonspatial cognitive activity
855 on postural stability. *Br. J. Psychol.* 92, 319–338. doi:10.1348/000712601162211.

856 Nakazawa, K., Kawashima, N., Obata, H., Yamanaka, K., Nozaki, D., Akai, M., 2003. Facilitation
857 of both stretch reflex and corticospinal pathways of the tibialis anterior muscle during standing
858 in humans. *Neurosci. Lett.* 338, 53–56. doi:10.1016/S0304-3940(02)01353-8.

859 Nasreddine, Z.S., Phillips, N.A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cum-
860 mings, J.L., Chertkow, H., 2005. The montreal cognitive assessment, MoCA: a brief screening
861 tool for mild cognitive impairment. *J. Am. Geriatr. Soc.* 53, 695–699. doi:10.1111/j.1532-
862 5415.2005.53221.x.

863 Noohi, F., Kinnaird, C., De Dios, Y., Kofman, I., Wood, S.J., Bloomberg, J.J., Mulavara, A.P.,
864 Sienko, K.H., Polk, T.A., Seidler, R.D., 2019. Deactivation of somatosensory and visual cor-
865 tices during vestibular stimulation is associated with older age and poorer balance. *PLoS one*
866 14, e0221954. doi:10.1371/journal.pone.0221954.

867 Noohi, F., Kinnaird, C., DeDios, Y., Kofman, I.S., Wood, S., Bloomberg, J., Mulavara, A., Seidler,
868 R., 2017. Functional brain activation in response to a clinical vestibular test correlates with
869 balance. *Front. Syst. Neurosci.* 11, 11. doi:10.3389/fnsys.2017.00011.

870 Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory.
871 *Neuropsychologia* 9, 97–113. doi:10.1016/0028-3932(71)90067-4.

872 Papegaaij, S., Taube, W., Baudry, S., Otten, E., Hortobágyi, T., 2014a. Aging causes a
873 reorganization of cortical and spinal control of posture. *Front. Aging Neurosci.* 6, 28.
874 doi:10.3389/fnagi.2014.00028.

875 Papegaaij, S., Taube, W., Hogenhout, M., Baudry, S., Hortobágyi, T., 2014b. Age-related de-
876 crease in motor cortical inhibition during standing under different sensory conditions. *Front.*
877 *Aging Neurosci.* 6, 126. doi:10.3389/fnagi.2014.00126.

878 Pasternak, O., Sochen, N., Gur, Y., Intrator, N., Assaf, Y., 2009. Free water elimination and
879 mapping from diffusion MRI. *Magn. Reson. Imaging* 62, 717–730. doi:10.1002/mrm.22055.

880 Patel, M., Magnusson, M., Kristinsdottir, E., Fransson, P.A., 2009. The contribution of
881 mechanoreceptive sensation on stability and adaptation in the young and elderly. *Eur. J.*
882 *Appl. Physiol.* 105, 167–173. doi:10.1007/s00421-008-0886-4.

883 Pearson, J.M., Heilbronner, S.R., Barack, D.L., Hayden, B.Y., Platt, M.L., 2011. Posterior

884 cingulate cortex: adapting behavior to a changing world. *Trends Cogn. Sci.* 15, 143–151.
885 doi:10.1016/j.tics.2011.02.002.

886 Peterka, R.J., 2002. Sensorimotor integration in human postural control. *J. Neurophysiol.* 88,
887 1097–1118. doi:10.1152/jn.2002.88.3.1097.

888 Piccinelli, M., 1998. Alcohol use disorders identification test (AUDIT). *Epidemiol. Psychiatr. Sci.*
889 7, 70–73.

890 Pierpaoli, C., Barnett, A., Pajevic, S., Chen, R., Penix, L., Virta, A., Basser, P., 2001. Water dif-
891 fusion changes in wallerian degeneration and their dependence on white matter architecture.
892 *NeuroImage* 13, 1174–1185. doi:10.1006/nimg.2001.0765.

893 Powell, L.E., Myers, A.M., 1995. The activities-specific balance confidence (ABC) scale. *J.*
894 *Gerontol. A Biol. Sci. Med. Sci.* 50, M28–M34. doi:10.1093/gerona/50A.1.M28.

895 Pupíková, M., Šimko, P., Gajdoš, M., Rektorová, I., 2021. Modulation of working memory and
896 resting-state fMRI by tDCS of the right frontoparietal network. *Neural Plast.* 2021. doi:10.
897 1155/2021/5594305.

898 R Core Team, X., 2013. R: A language and environment for statistical computing .

899 Rankin, J.K., Woollacott, M.H., Shumway-Cook, A., Brown, L.A., 2000. Cognitive influence on
900 postural stability: a neuromuscular analysis in young and older adults. *J. Gerontol. A Biol.*
901 *Sci. Med. Sci.* 55, M112–M119. doi:10.1093/gerona/55.3.M112.

902 Røgind, H., Lykkegaard, J., Bliddal, H., Danneskiold-Samsøe, B., 2003. Postural sway in normal
903 subjects aged 20–70 years. *Clin. Physiol. Funct. Imaging* 23, 171–176. doi:10.1046/j.1475–
904 097X.2003.00492.x.

905 Romero, J.E., Coupé, P., Giraud, R., Ta, V.T., Fonov, V., Park, M.T.M., Chakravarty, M.M.,
906 Voineskos, A.N., Manjón, J.V., 2017. CERES: a new cerebellum lobule segmentation method.
907 *NeuroImage* 147, 916–924. doi:10.1016/j.neuroimage.2016.11.003.

908 Rosano, C., Aizenstein, H.J., Studenski, S., Newman, A.B., 2007. A regions-of-interest volu-
909 metric analysis of mobility limitations in community-dwelling older adults. *J. Gerontol. A Biol.*
910 *Sci. Med. Sci.* 62, 1048–1055. doi:10.1093/gerona/62.9.1048.

911 Rosenthal, R., Cooper, H., Hedges, L., et al., 1994. Parametric measures of effect size. *Hand-
912 book Res. Synth.* 621, 231–244.

913 Ryberg, C., Rostrup, E., Stegmann, M.B., Barkhof, F., Scheltens, P., van Straaten, E.C.,
914 Fazekas, F., Schmidt, R., Ferro, J., Baezner, H., et al., 2007. Clinical significance of
915 corpus callosum atrophy in a mixed elderly population. *Neurobiol. Aging* 28, 955–963.
916 doi:10.1016/j.neurobiolaging.2006.04.008.

917 Salat, D.H., Buckner, R.L., Snyder, A.Z., Greve, D.N., Desikan, R.S., Busa, E., Morris, J.C.,
918 Dale, A.M., Fischl, B., 2004. Thinning of the cerebral cortex in aging. *Cereb. Cortex.* 14,
919 721–730. doi:10.1093/cercor/bhh032.

920 Salazar, A.P., Hupfeld, K.E., Lee, J.K., Banker, L.A., Tays, G.D., Beltran, N.E., Kofman, I.S.,
921 De Dios, Y.E., Mulder, E., Bloomberg, J.J., et al., 2021. Visuomotor adaptation brain changes
922 during a spaceflight analog with elevated carbon dioxide (CO₂): A pilot study. *Front. in Neural*
923 *Circuits* 15, 51. doi:10.3389/fncir.2021.659557.

924 Salazar, A.P., Hupfeld, K.E., Lee, J.K., Beltran, N.E., Kofman, I.S., De Dios, Y.E., Mulder, E.,
925 Bloomberg, J.J., Mulavara, A.P., Seidler, R.D., 2020. Neural working memory changes dur-
926 ing a spaceflight analog with elevated carbon dioxide: a pilot study. *Frontiers in Systems*
927 *Neuroscience* 14, 48. doi:10.3389/fnsys.2020.00048.

928 Seidler, R.D., Bernard, J.A., Burutolu, T.B., Fling, B.W., Gordon, M.T., Gwin, J.T., Kwak, Y.,
929 Lipps, D.B., 2010. Motor control and aging: links to age-related brain structural, functional,
930 and biochemical effects. *Neurosci. Biobehav. Rev.* 34, 721–733. doi:10.1016/j.neubiorev.
931 2009.10.005.

932 Shumway-Cook, A., Horak, F.B., 1986. Assessing the influence of sensory interaction on bal-
933 ance: suggestion from the field. *Phys. Ther.* 66, 1548–1550. doi:10.1093/ptj/66.10.1548.

934 Smith, S.M., Jenkinson, M., Johansen-Berg, H., Rueckert, D., Nichols, T.E., Mackay, C.E.,
935 Watkins, K.E., Ciccarelli, O., Cader, M.Z., Matthews, P.M., et al., 2006. Tract-based spatial
936 statistics: voxelwise analysis of multi-subject diffusion data. *NeuroImage* 31, 1487–1505.
937 doi:10.1016/j.neuroimage.2006.02.024.

938 Smith, S.M., Jenkinson, M., Woolrich, M.W., Beckmann, C.F., Behrens, T.E., Johansen-Berg,
939 H., Bannister, P.R., De Luca, M., Drobniak, I., Flitney, D.E., et al., 2004. Advances in functional
940 and structural MR image analysis and implementation as FSL. *NeuroImage* 23, S208–S219.
941 doi:10.1016/j.neuroimage.2004.07.051.

942 Song, S.K., Sun, S.W., Ju, W.K., Lin, S.J., Cross, A.H., Neufeld, A.H., 2003. Diffusion tensor
943 imaging detects and differentiates axon and myelin degeneration in mouse optic nerve after
944 retinal ischemia. *NeuroImage* 20, 1714–1722. doi:10.1016/j.neuroimage.2003.07.005.

945 Starr, J.M., Leaper, S., Murray, A.D., Lemmon, H., Staff, R.T., Deary, I.J., Whalley, L.J., 2003.
946 Brain white matter lesions detected by magnetic resonance imaging are associated with bal-
947 ance and gait speed. *J. Neurol. Neurosurg. Psychiatry* 74, 94–98. doi:10.1136/jnnp.74.1.
948 94.

949 Stelmach, G.E., Teasdale, N., Di Fabio, R.P., Phillips, J., 1989. Age related decline in postural
950 control mechanisms. *Int. J. Aging Hum. Dev.* 29, 205–223. doi:10.2190/KKP0-W3Q5-6RDN-
951 RXYT.

952 Sullivan, E.V., Rohlfing, T., Pfefferbaum, A., 2010. Quantitative fiber tracking of lateral and
953 interhemispheric white matter systems in normal aging: relations to timed performance. *Neu-
954 robiol. Aging* 31, 464–481. doi:10.1016/j.neurobiolaging.2008.04.007.

955 Sullivan, E.V., Rose, J., Rohlfing, T., Pfefferbaum, A., 2009. Postural sway reduction in aging
956 men and women: relation to brain structure, cognitive status, and stabilizing factors. *Neuro-
957 biol. Aging* 30, 793–807. doi:10.1016/j.neurobiolaging.2007.08.021.

958 Sulpizio, V., Committeri, G., Lambrey, S., Berthoz, A., Galati, G., 2013. Selective role of
959 lingual/parahippocampal gyrus and retrosplenial complex in spatial memory across view-

960 point changes relative to the environmental reference frame. *Behav. Brain Res.* 242, 62–75.
961 doi:10.1016/j.bbr.2012.12.031.

962 Taube, W., Gruber, M., Gollhofer, A., 2008. Spinal and supraspinal adaptations associated with
963 balance training and their functional relevance. *Acta Physiologica* 193, 101–116. doi:10.
964 1111/j.1748-1716.2008.01850.x.

965 Teasdale, N., Stelmach, G., Breunig, A., Meeuwsen, H., 1991. Age differences in visual sensory
966 integration. *Exp. Brain Res.* 85, 691–696.

967 Tell, G.S., Lefkowitz, D.S., Diehr, P., Elster, A.D., 1998. Relationship between balance and
968 abnormalities in cerebral magnetic resonance imaging in older adults. *Arch. Neurol.* 55, 73–
969 79. doi:10.1001/archneur.55.1.73.

970 Thambisetty, M., Wan, J., Carass, A., An, Y., Prince, J.L., Resnick, S.M., 2010. Longitudinal
971 changes in cortical thickness associated with normal aging. *NeuroImage* 52, 1215–1223.
972 doi:10.1016/j.neuroimage.2010.04.258.

973 Tinetti, M.E., Richman, D., Powell, L., 1990. Falls efficacy as a measure of fear of falling. *J.*
974 *Gerontol.* 45, P239–P243. doi:10.1093/geronj/45.6.P239.

975 Van Impe, A., Coxon, J.P., Goble, D.J., Doumas, M., Swinnen, S.P., 2012. White matter frac-
976 tional anisotropy predicts balance performance in older adults. *Neurobiol. Aging* 33, 1900–
977 1912. doi:10.1016/j.neurobiolaging.2011.06.013.

978 Vander Wyk, B.C., Hudac, C.M., Carter, E.J., Sobel, D.M., Pelpfrey, K.A., 2009. Ac-
979 tion understanding in the superior temporal sulcus region. *Psychol. Sci.* 20, 771–777.
980 doi:10.1111/j.1467-9280.2009.02359.x.

981 Varghese, J.P., Beyer, K.B., Williams, L., Miyasike-daSilva, V., McIlroy, W.E., 2015. Standing
982 still: is there a role for the cortex? *Neurosci. Lett.* 590, 18–23. doi:10.1016/j.neulet.2015.
983 01.055.

984 Venables, W.N., Ripley, B.D., et al., 1999. Modern applied statistics with s-plus .

985 Vestito, L., Rosellini, S., Mantero, M., Bandini, F., 2014. Long-term effects of transcranial direct-
986 current stimulation in chronic post-stroke aphasia: a pilot study. *Front. Hum. Neurosci.* 8, 785.
987 doi:10.3389/fnhum.2014.00785.

988 Vos, S.B., Tax, C.M., Luijten, P.R., Ourselin, S., Leemans, A., Froeling, M., 2017. The im-
989 portance of correcting for signal drift in diffusion MRI. *Magn. Reson. Imaging* 77, 285–299.
990 doi:10.1002/mrm.26124.

991 Wakana, S., Caprihan, A., Panzenboeck, M.M., Fallon, J.H., Perry, M., Gollub, R.L., Hua, K.,
992 Zhang, J., Jiang, H., Dubey, P., et al., 2007. Reproducibility of quantitative tractography meth-
993 ods applied to cerebral white matter. *NeuroImage* 36, 630–644. doi:10.1016/j.neuroimage.
994 2007.02.049.

995 Woollacott, M.H., Shumway-Cook, A., Nashner, L.M., 1986. Aging and posture control:
996 changes in sensory organization and muscular coordination. *Int. J. Aging Hum. Dev.* 23,
997 97–114. doi:10.2190/VXN3-N3RT-54JB-X16X.

998 Yosephi, M.H., Ehsani, F., Zoghi, M., Jaberzadeh, S., 2018. Multi-session anodal tDCS enhances
999 the effects of postural training on balance and postural stability in older adults with high fall
1000 risk: primary motor cortex versus cerebellar stimulation. *Brain Stimul.* 11, 1239–1250. doi:10.
1001 1016/j.brs.2018.07.044.

1002 Yotter, R.A., Dahnke, R., Thompson, P.M., Gaser, C., 2011a. Topological correction of brain
1003 surface meshes using spherical harmonics. *Hum. Brain Mapp.* 32, 1109–1124. doi:10.1002/
1004 hbm.21095.

1005 Yotter, R.A., Nenadic, I., Ziegler, G., Thompson, P.M., Gaser, C., 2011b. Local cortical surface
1006 complexity maps from spherical harmonic reconstructions. *NeuroImage* 56, 961–973. doi:10.
1007 1016/j.neuroimage.2011.02.007.

1008 Yun, H.J., Im, K., Yang, J.J., Yoon, U., Lee, J.M., 2013. Automated sulcal depth measurement
1009 on cortical surface reflecting geometrical properties of sulci. *PLoS One* 8, e55977. doi:10.
1010 1371/journal.pone.0055977.

1011 Yushkevich, P.A., Piven, J., Hazlett, H.C., Smith, R.G., Ho, S., Gee, J.C., Gerig, G., 2006.
1012 User-guided 3D active contour segmentation of anatomical structures: significantly improved
1013 efficiency and reliability. *NeuroImage* 31, 1116–1128. doi:10.1016/j.neuroimage.2006.01.
1014 015.