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# Mechanical Properties of the Cortex in Older Adults and Relationships With Personality Traits

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## ABSTRACT

Aging and neurodegeneration impact structural brain integrity and can result in changes to behavior and cognition. Personality, a relatively stable trait in adults as compared to behavior, in part relies on normative individual differences in cellular organization of the cerebral cortex, but links between brain structure and personality expression have been mixed. One key finding is that personality has been shown to be a risk factor in the development of Alzheimer's disease, highlighting a structure–trait relationship. Magnetic resonance elastography (MRE) has been used to noninvasively study age-related changes in tissue mechanical properties because of its high sensitivity to both the microstructural health and the structure–function relationship of the tissue. Recent advancements in MRE methodology have allowed for reliable property recovery of cortical subregions, which had previously presented challenges due to the complex geometry and overall thin structure. This study aimed to quantify age-related changes in cortical mechanical properties and the relationship of these properties to measures of personality in an older adult population ($N = 57$; age 60–85 years) for the first time. Mechanical properties including shear stiffness and damping ratio were calculated for 30 bilateral regions of the cortex across all four lobes, and the NEO Personality Inventory (NEO-PI) was used to measure neuroticism and conscientiousness in all participants. Shear stiffness and damping ratio were found to vary widely across regions of the cortex, upward of 1 kPa in stiffness and by 0.3 in damping ratio. Shear stiffness changed regionally with age, with some regions experiencing accelerated degradation compared to neighboring regions. Greater neuroticism (i.e., the tendency to experience negative emotions and vulnerability to stress) was associated with high damping ratio, indicative of poorer tissue integrity, in the rostral middle frontal cortex and the precentral gyrus. This study provides evidence of structure–trait correlates between physical mechanical properties and measures of personality in older adults and adds to the supporting literature that neurotic traits may impact brain health in cognitively normal aging.

## 1 | Introduction

In the brain, changes to tissue structure and composition occur in both healthy aging and age-related neurodegenerative conditions. In the case of Alzheimer's disease, degradation in the brain is linked to functional impairments, such as memory dysfunction, and can lead to long term emotional and financial burden on the patient and caregiver(s) and increased strain on the medical system (Mouton et al. 1998; Pini et al. 2016; Wilson et al. 2012). Standard imaging MRI techniques have been used to measure volume loss and cortical thinning as a method for studying aging and neurodegeneration in the brain (Fjell and Walhovd 2010; Lockhart and DeCarli 2014); however, these morphological measures are only indirectly related to the biological changes happening on the microstructural level that are not captured by standard techniques. This has created inconsistencies in apparent magnitude of age-related degradation and the location of where the most degradation is occurring (Fjell, Westlye, et al. 2009), highlighting the opportunity to study tissue microstructural properties directly to provide increased sensitivity to early or more subtle changes with age. In the cortex specifically, additional work is needed to study variation in age-related structural changes, especially given that individual cortical subregions are associated with specific behaviors, traits, and processes.

Personality is a unique set of traits that shape how a person adapts to life, encompassing their behavior, interests, values, cognitive patterns, and emotional tendencies. Previous studies have shown that personality traits are relatively stable, with only moderate changes across the lifespan, especially as children move into adulthood, but that they do not change significantly in middle age or beyond (Costa, McCrae, and Löckenhoff 2019; Debast et al. 2014; Roberts and DelVecchio 2000; Terracciano, Costa, and McCrae 2006). Dimensions of personality, specifically neuroticism, have also been reported as risk factors for Alzheimer's disease, indicating possible microstructural level changes happening in associated regions well before detectable degeneration occurs (Segerstrom 2020; Terracciano et al. 2014). While the specifics regarding the association between personality and Alzheimer's disease are unknown, researchers hypothesize that either personality can create a predisposition for Alzheimer's disease through behavioral choices that create negative consequences for brain health or that personality can create inflammation driving a pathoplastic response (Segerstrom 2020). Conscientiousness, one of the five major personality domains along with neuroticism, has also been linked to brain structure in the frontal lobe, particularly, the orbitofrontal and prefrontal cortices (Lewis et al. 2018; Riccelli et al. 2017). However, studies considering structure–trait relationships in the cortex to identify the neuroanatomical correlates of personality traits are hampered by apparent low sensitivity of common neuroimaging techniques. For example, recent reviews have noted inconsistent results among studies relying on volumetric MRI (Avinun et al. 2020; Chen and Canli 2022). For studying both age-related brain tissue degeneration and structure–trait relationships in the cortex, improved imaging techniques are needed to more sensitively assess the tissue of interest.

A recent technique that adds sensitivity to studying the structure of the brain is magnetic resonance elastography (MRE) (Muthupillai et al. 1995). MRE utilizes phase contrast imaging to estimate the mechanical properties of a tissue of interest (Manduca et al. 2001). Frequently reported properties are shear stiffness and damping ratio, which aim to quantify structural integrity of the tissue and are sensitive to changes on the microstructural scale (Manduca et al. 2021; Sack et al. 2013). Both stiffness and damping ratio have been shown to dynamically change during periods of known structural remodeling in the brain including growth and development, aging, and neurological disease onset (Hiscox et al. 2021; McIlvain et al. 2022). When considering advancement into older age specifically, widespread softening is seen across the brain, with the magnitude of age-related softening being dependent on region (Hiscox et al. 2021). Changes in shear stiffness have been shown to align with notable age-related effects present during this period including myelin degradation (Schregel et al. 2012). In the specific case of neurodegeneration seen with aging, MRE has shown to be sensitive to typical aging, mild cognitive impairment, and Alzheimer's disease, with accelerated softening seen in the latter cases (Delgorio et al. 2023; Hiscox et al. 2018; Hiscox, Johnson, McGarry, Marshall, et al. 2020; Hiscox 2018; Murphy et al. 2011, 2016; Pavuluri et al. 2023; Sack et al. 2009, 2011) presumably due to the hallmark pathology known to occur with the disease (Munder et al. 2018).

Until recently, work using MRE has been limited to studying the cortex as a larger region without significant regional differentiation (Hiscox, McGarry, and Johnson 2022). This has limited the utility of MRE as a tool for investigating the ways in which the mechanical properties of distinct anatomical regions of the cortex may contribute to neuropsychological outcomes. Due to the small size of individual cortical subregions, the complex geometry of these regions, and the proximity of these regions to both the stiffer white matter and neighboring cerebrospinal fluid (CSF), established MRE processing algorithms proved insufficient to resolve individual cortical structures. Recent technique advancements have overcome these limitations and improved scan resolution. For small, challenging regions, additional parameters are added to the inversion algorithm to prioritize homogeneity within the region and limit the influence of surrounding tissue and CSF on property estimates, which was validated by Hiscox, McGarry, and Johnson (2022). These advancements allow for reliable property recovery in small subregions, which is of particular interest for studying the associations between mechanical properties of these regions alongside personality traits.

Notably, MRE has shown promise in providing unique insight into structure–function relationships in the brain, with an emphasis on the relationship between mechanical properties of the hippocampus and performance on behavioral tests of memory function (Delgorio et al. 2022; Hiscox, Johnson, McGarry, Schwarb, et al. 2020; Johnson et al. 2018; Pavuluri et al. 2024; Schwarb et al. 2016, 2017, 2019). Furthermore, differences in the impact of aging on the mechanical properties of hippocampal subfields have been identified (Delgorio et al. 2021), and these changes were also linked to memory performance (Delgorio et al. 2022), showing that mechanical structure–function relationships in the brain can be identified in small anatomical regions by using high-resolution MRE with specialized inversion methods. Given the variability in both structure and function of the cortex, there is interest in understanding if similar regional differences are present during the healthy aging process and how this impacts the function of the cortex. Preliminary studies have observed associations between MRE of cortical regions and risk-taking behavior and fluid intelligence measures (Johnson et al. 2018; McIlvain et al. 2020), which can be enhanced with methods optimized for the cortex.

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The purpose of this cross-sectional study was to (1) determine the regional effects of aging on the mechanical properties of the cortex and (2) examine the relationship between regional mechanical properties and personality traits, which reflect a relatively stable and characteristic pattern of thoughts, feelings, and behaviors. Specifically, we examined associations with neuroticism and conscientiousness from the NEO Personality Inventory (NEO-PI). We hypothesized that apparent age-related softening would been seen across the cortical regions, but the magnitude of softening would vary by region and highlight the regions that experience accelerated degradation. Based on prior work we hypothesized that dimensions of personality would be linked to differences in mechanical properties in the frontal lobe: particularly in the medial prefrontal cortex, anterior cingulate gyrus, and precentral cortex, which previous work has identified as structural correlates of personality (Mincic 2015; Ormel et al. 2013; Owens et al. 2019; Servaas et al. 2013). Also, it was expected based on previous work that shear stiffness would be sensitive to aging effects, while damping ratio would capture individual differences in personality and behavior.

## 2 | Methods

### 2.1 | Participants

Fifty-seven healthy older adults completed both an imaging session on a 3T Siemens Prisma MRI scanner with 64-channel head coil (Siemens Medical Solutions; Erlangen, Germany) and a behavioral assessment. Participants were aged 60–85 years (mean: $69 \pm 5.6$ years, 18 male/39 female). All participants were screened for previous history of neurological conditions, head trauma, and contraindications for receiving an MRI (including claustrophobia, metal implants, pregnancy). This study was approved by the Institutional Review Board at the University of Delaware. All participants reviewed the study protocol and provided written informed consent.

### 2.2 | MRI Collection and Processing

The MRI session included both structural and MRE scans. MRE involves delivering vibrations to the occipital portion of the head, which creates micron level displacements that are imaged using a phase contrast MRI sequence. Vibrations for the MRE sequence were applied at 50 Hz using a pneumatic actuator (Resoundant; Rochester, Minnesota), as shown in Figure 1. High resolution MRE data were collected following the protocol detailed by Delgorio et al. (2021) using a 3D multiband, multishot spiral MRE sequence with 1.25 mm$^3$ isotropic resolution (Johnson, Holtrop, et al. 2016). Imaging parameters included: $240 \times 240$ mm$^2$ field of view, $192 \times 192$ imaging matrix, 96 slices, 1.25 mm slice thickness, TR/TE = 3360/70 ms, with a total scan time of 10 min 45 s.

The structural scan was a T1-weighted MPRAGE (magnetization prepared rapidly acquired gradient echo) with a resolution of $0.9 \times 0.9 \times 0.9$ mm$^3$ (TE: 2.32 ms, TR: 1900 ms, and TI: 900 ms). The T1-weighted MPRAGE was segmented into anatomical regions with FreeSurfer to obtain binary masks of the regions of interest (Fischl 2012). A total of 30 regions covering the entire cerebral cortex were extracted following the Desikan–Killiany Atlas and assessed bilaterally (Desikan et al. 2006). Several example regions of interest are shown in Figure 2 overlayed on MRE property maps. Regional volume and cortical thickness measures were generated from FreeSurfer to use as morphometric measures for comparison with MRE.

### 2.3 | Mechanical Property Estimation With Nonlinear Inversion

Displacement data obtained from the MRE scan was used to calculate tissue mechanical properties using the nonlinear inversion algorithm (NLI) (McGarry et al. 2012). To reliably recover properties from the cortex regions, we applied spatial filtering and soft prior regularization (SPR) in accordance with the protocol described by Hiscox, McGarry, and Johnson (2022). The spatial filtering parameter in NLI was set to 0.9 mm, which reduces smoothing across subzones between global iterations in comparison with higher values (Delgorio et al. 2021). This low spatial filtering value reduces regularization and smoothing of estimated properties across the cortex and is achievable due to the small voxel size of the MRE data collected. SPR (McGarry et al. 2012) is also used during NLI and reduces influence from neighboring tissues by promoting local homogeneity in a predefined region (Johnson, Schwarb, et al. 2016). Together, these parameters help to recover individual cortical regions from among the much stiffer white matter tissue and much softer

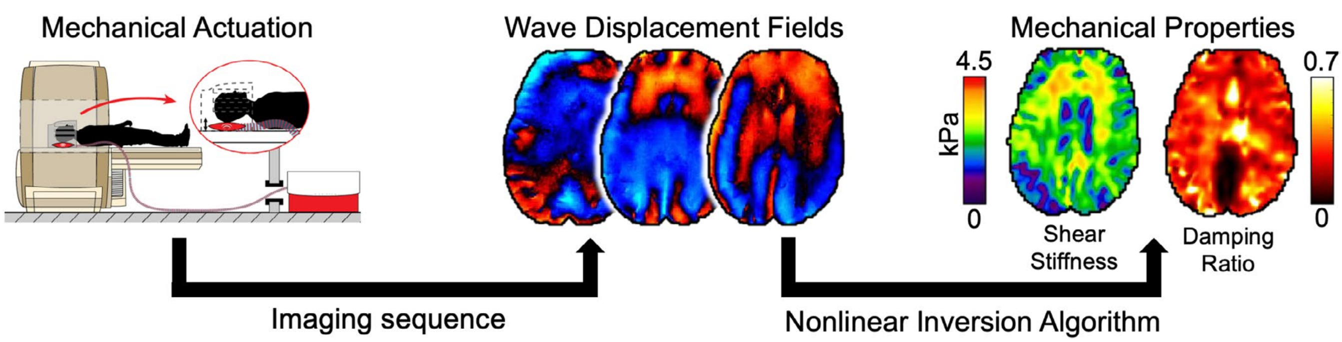


**FIGURE 1** | MRE imaging protocol starts with mechanical actuation shown on the far left. Displacements (shown in *X*, *Z*, and *Y* directions, respectively) due to the induced vibrations are captured using a custom imaging sequence with motion encoding gradients. A nonlinear inversion algorithm is then used to solve for the mechanical properties of the tissue and create whole brain property maps.

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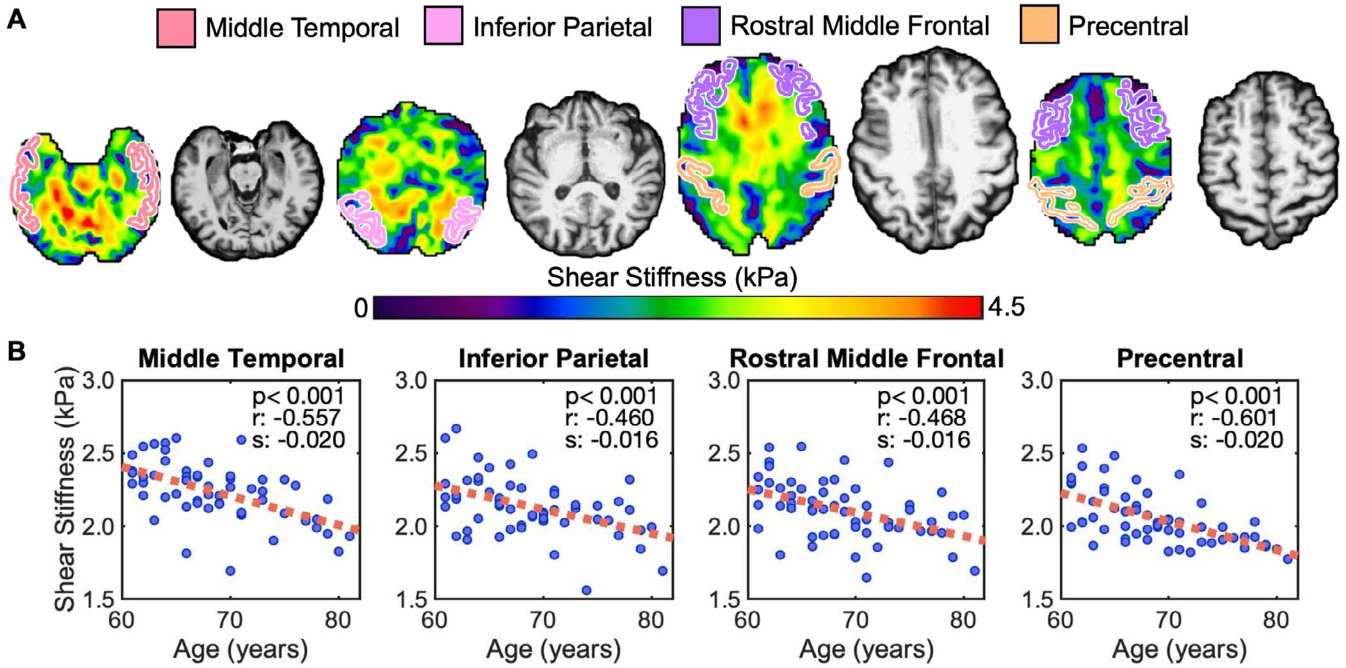


**FIGURE 2** | (A) Regions of interest overlayed on MRE stiffness maps next to the corresponding anatomical image. (B) Representative plots showing the relationship between stiffness and age cross-sectionally across the study population for the regions displayed above. Participants are denoted by individual points with the best fit line indicating average yearly stiffness loss plotted as the overlayed dash line. In the upper right corner is displayed the significance of the correlation between age and stiffness ($p$), the correlation coefficient of the age and stiffness relationship ($r$), and slope of the stiffness and age relationship in kPa/year (s).

cerebrospinal fluid, while still providing a stable result. Binary masks of individual, unilateral cortical regions from FreeSurfer were provided to SPR after co-registering the T1-weighted MPRAGE to the MRE images using FLIRT in FSL (Jenkinson et al. 2002, 2012). SPR is applied through the NLI cost function with a weighting of $\alpha = 10^{-12}$, per recommendation by Hiscox, McGarry, and Johnson (2022) for cortical MRE.

The output of NLI is the complex shear modulus, defined by $G^* = G' + iG''$ (Hiscox et al. 2016). The complex shear modulus comprises both the real and imaginary components that are commonly referred to as the storage and loss moduli, $G'$ and $G''$, respectively. From $G^*$, shear stiffness was calculated using the following equation, $\mu = 2|G^*|^2/(G' + |G^*|)$. Damping ratio is also calculated following the equation $\xi = G'' / 2G'$. Data quality is confirmed using octahedral shear strain signal-to-noise ratio (OSS-SNR) (McGarry et al. 2011), with a minimum OSS-SNR of 3.0 required to generate recoverable, reliable property maps. Mechanical properties of each cortical region were then obtained by averaging the property maps generated over the specific regions as defined by the masks obtained from FreeSurfer. We primarily consider cortical regions bilaterally by averaging regions from the left and right hemispheres together.

### 2.4 | Personality Assessment

Participants also completed a behavioral session that included the NEO-PI to measure the five major domains of personality (Costa and McCrae 1992; Sutin et al. 2023). We focused our analysis on two of these measures, neuroticism and conscientiousness, because of their association with neurodegenerative conditions and frontal lobe structure. Neuroticism is classified as the tendency to experience negative emotion and vulnerability to stress, with high scores indicating more susceptibility to negative emotions and stress (Sutin et al. 2023). Conscientiousness, reflecting organized, disciplined, and responsible behaviors, has a positive classification with higher scores representing positive emotions and behaviors (Costa and McCrae 1992). The NEO-PI comprises 60 questions. For each question, participants select the appropriate response regarding aspects of their personality with answers ranging from "strongly disagree" to "strongly agree" following a 1–5 Likert Scale. Reversal questions are included (to detect inattentive respondents) and for these the scaling is switched before tabulating the final scores for each personality domain.

### 2.5 | Statistical Analysis

We aimed to (1) determine the relationships between age and the mechanical properties of individual regions of the cortex and (2) assess the relationship between regional mechanical properties of the frontal cortex and personality measures in older adults. The stiffness and damping ratio of cortical regions were investigated separately. In SPSS v29.0 (IBM; Armonk, NY), a linear mixed model with repeated measures, controlling for sex, was and used to determine if there was a significant difference in stiffness with age and if this relationship differed across the cortex (i.e., age × region interaction); the same analysis was repeated with damping ratio. Omnibus effects found in the linear mixed models were further investigated by correlating stiffness or damping ratio for each region individually, when applicable. Significance of all correlations were adjusted for multiple comparisons using a Bonferroni–Holm correction (Holm 1979). Steiger's $z$-test was used to compare the effects of age across regions when a significant age × region interaction was present (Steiger 1980). For changes with age, we also calculated the average annual stiffness loss as the slope of the best fit line, as shown in Figure 2B, and used this to evaluate average mechanical properties at 75 years. For comparison, we also performed the same analysis for cortical thickness as an assessment of regional structure. We examined relationships between the associations of mechanical properties with age and cortical thickness with age across the regions of interest to understand if these two structural measures varied together in older adults.

To assess the relationship between personality and mechanical properties, we a priori selected regions of the frontal lobe based on previous research. These regions make up the medial prefrontal cortex (superior frontal cortex, medial orbitofrontal cortex, lateral orbitofrontal cortex, rostral middle frontal cortex), the anterior cingulate cortex (rostral anterior cingulate, caudal anterior cingulate), and the precentral gyrus (Lai et al. 2019; Mincic 2015; Ormel et al. 2013; Servaas et al. 2013; Wright et al. 2006). We then applied a regression model in StataSE 17.0 (StataCorp; College Station, TX) to test if mechanical properties of brain tissue are predictive of neuroticism and conscientiousness. This analysis was completed for both shear stiffness and damping ratio—controlling for age and sex, and cortical thickness was also tested for comparison. All data were checked for regression assumptions of homoscedasticity, normalness, skewness, and kurtosis. A robust regression was used when applicable assumptions were violated and is noted within the results. A traditional yet conservative Bonferroni correction was applied to account for multiple comparisons (Bland and Altman 1995). A Romano–Wolf correction was also applied because this method takes into account the dependence structure of the test statistics by resampling from the original data (e.g., bootstrapping) to control the familywise error rate, thereby increasing power and reducing the over-rejection of null hypotheses (Clarke, Romano, and Wolf 2019).

## 3 | Results

The population of older adult participants studied exhibited significant regional variation in shear stiffness and damping ratio across the individual regions of cortex. Figure 3A illustrates average regional stiffness for each cortical region evaluated at 75 years, which varied from 1.87 kPa in the temporal pole to 2.95 kPa in the lingual cortex. Cortical regions varied in damping ratio from 0.10 in the posterior cingulate to 0.41 in the temporal pole and exhibited similar heterogeneity across the brain as stiffness. Tables S1 and S2 collect the average stiffness and damping ratio of each cortical region evaluated at 75 years, respectively.

We found a significant main effect of age on stiffness of cortical regions, such that advanced age was associated with lower cortical stiffness in our population of older adult subjects ($p < 0.001$). The average age-related rate of change calculated across the cross-sectional population for all cortical regions was −0.016 kPa/year. Stiffness of individual cortical regions changed differently with age, as evidenced by a significant age × region interaction effect ($p < 0.001$) and can be seen in the plots of representative regions in Figure 2B. Of the 30 bilateral cortical regions examined, 18 exhibited significant negative relationships between regional stiffness and age. Significant annual stiffness declines, illustrated in Figure 3B, ranged between −0.01 and −0.03 kPa/year, with the largest age-related softening effects in the caudal anterior cingulate (−0.030 kPa/year; $r = -0.450$; $p < 0.001$), the posterior cingulate (−0.028 kPa/year; $r = -0.606$; $p < 0.001$), and the insula (−0.023 kPa/year; $r = -0.541$; $p < 0.001$). The age-related softening effect did not appear to correlate with overall region stiffness (i.e., higher initial stiffness did not lead to greater declines with age); for example, in the occipital lobe both the lingual cortex and cuneus exhibited rates of −0.021 kPa/year, but their average stiffness differed by 0.6 kPa (lingual 2.95 kPa, cuneus 2.35 kPa). Large differences in age-related softening were also seen in directly neighboring regions, such as the precentral gyrus (−0.020 kPa/year; $r = -0.601$, $p < 0.001$) and paracentral gyrus (−0.010 kPa/year, $r = -0.271$, $p > 0.05$) with a Steiger $z$-score of 2.56 ($p < 0.001$) indicating the relationships of stiffness with age between these two regions are significantly different. Table S1 contains relationships between stiffness and age for each region and Table S3 includes the Steiger $z$-test results comparing each of the stiffness–age relationships between regions.

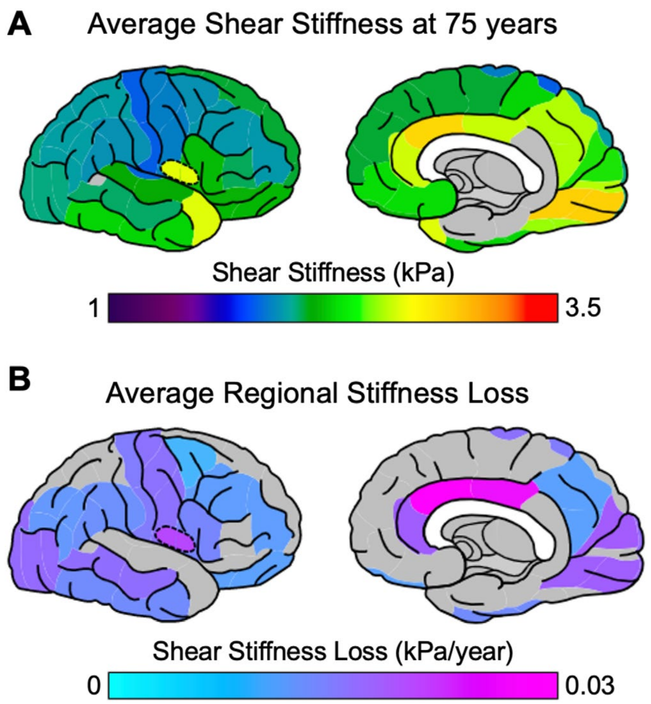


**FIGURE 3** | (A) Average shear stiffness for each bilateral cortical region was evaluated at 75 years old. (B) Average stiffness loss in kPa/year for each cortical region exhibiting a significant relationship with age; greater stiffness loss per year is represented by warmer colors. The brain graphics were created with the Simple Brain Plot Toolbox (Scholtens, de Lange, and van den Heuvel 2021).

In contrast, damping ratio of the cortex did not change significantly with age ($p > 0.05$ main effect from omnibus test), nor did individual regions exhibit significantly different age-related changes in

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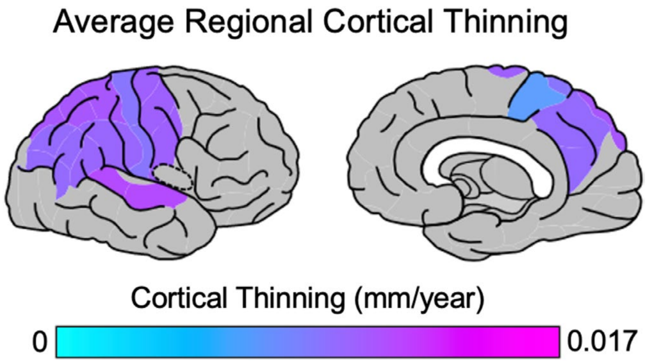


**FIGURE 4** | Regions exhibiting significant cortical thinning with age. Greater age-related differences are represented by warmer colors.

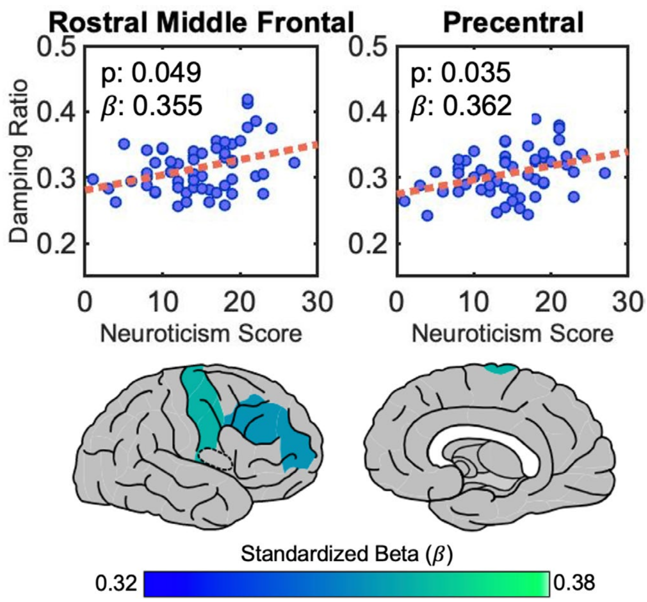


**FIGURE 5** | For visualization, plots illustrating significant relationships between neuroticism and damping ratio in the rostral middle frontal cortex and precentral gyrus. Each plot includes all participants plotted as points with a line of best fit overlayed as the dashed line. The Bonferroni corrected $p$-value and standardized $\beta$ are displayed in the upper left corner. These regions are shown anatomically in the bottom right with the color of each region indicating the magnitude of the standardized $\beta$, where brighter green indicates a stronger relationship between the regional damping ratio and the neuroticism score).

damping ratio ($p > 0.05$ interaction effect). Table S2 contains the relationships between damping ratio and age for each region.

We also performed a similar analysis using the morphological measures of cortical thickness to compare to our mechanical property results. In comparison, cortical thinning did not show similar age-related results when compared to stiffness. Only eight regions exhibited significant relationships with age, with significant thinning ranging from 0.006 mm/year in the paracentral gyrus ($r = -0.499$; $p < 0.001$) to 0.012 mm/year in the superior temporal gyrus ($r = -0.451$; $p < 0.001$). Figure 4 illustrates the cortical regions exhibiting significant relationships between thickness and age for visual comparison with the stiffness results seen in Figure 3B. Table S4 presents all relationships between cortical thickness and age. We additionally correlated the age-related stiffness effects with the age-related cortical thickness effects, and found that age effects in these properties did not significantly vary together across the cortical regions ($p = 0.43$).

We compared the mechanical properties of each cortical region with the score of both domains of personality considered—neuroticism and conscientiousness—controlling for age. Testing our a priori hypothesis in seven regions of the frontal lobe, we found that damping ratio predicted neuroticism scores in two regions: the precentral gyrus and rostral middle frontal, seen in Figure 5. The results across all seven regions are shown in Table 1, where higher damping ratio was associated with greater neuroticism. It is important to note that neuroticism was not correlated with age in our participant population ($r = 0.01$; $p = 0.933$). Damping ratio across all seven regions was not significantly predictive of conscientiousness (all $p > 0.05$), as seen in Table S5. For stiffness, none of the a priori regions were significantly correlated with either measure of personality traits (all $p > 0.05$). These results for neuroticism and conscientiousness can be found in Tables S6 and S7, respectively. Cortical thickness was not predictive of neuroticism in any region with full results shown in Table S8. However, cortical thickness was significantly predictive of conscientiousness in the medial orbitofrontal ($p = 0.021$) and caudal anterior cingulate ($p = 0.035$). Table S9 contains these results, where a thicker cortex was predictive of higher conscientiousness scores.

Bilateral regions exhibiting significant correlation between damping ratio and neuroticism or cortical thickness and conscientiousness were further analyzed unilaterally with regions of both left and right hemispheres correlated with the respective trait. The correlation coefficient and the uncorrected significance can be found in Tables S10 and S11. For the rostral middle frontal and precentral both the left and right sides of these regions had significant relationships between damping ratio and neuroticism scores, consistent with the bilateral region. However, there were differences in the correlations effect size for the precentral gyrus (left: $r = 0.27$, $p = 0.045$ vs. right: $r = 0.38$, $p = 0.004$), but minimal difference for the rostral middle frontal (left: $r = 0.33$, $p = 0.012$ vs. right: $r = 0.31$, $p = 0.020$). In the medial orbitofrontal cortex, only right hemisphere damping ratio exhibited a significant relationship with neuroticism ($r = 0.40$, $p = 0.002$). For cortical thickness, the caudal anterior cingulate thickness was significantly related to conscientiousness scores on both side with varying correlation strengths (left: 0.347 and right: 0.279).

## 4 | Discussion

In the current study, we characterized associations in regional mechanical properties of the cortex with age and personality traits in older adults. Here, we expand on previous work by showing that brain stiffness is negatively associated with age, not only globally, but in small subregions of the cortex and that age-related changes varied across these regions (Arani et al. 2015; Hiscox et al. 2021). This analysis was enabled in part by our high-resolution imaging and analysis protocols designed to improve reliability of cortical MRE measures (Delgorio et al. 2021; Hiscox, McGarry, and Johnson 2022). We also show that damping ratio of key cortical regions exhibited relationships with personality for the first time, where higher damping

**TABLE 1** | Associations between neuroticism scores and damping ratio, $\xi$, in cortical regions of the frontal lobe, adjusting for age and sex.

| Region | Standardized $\beta$ | $p$ uncorrected | $p$ (Bonferroni) | $p$ (Romano–Wolf) |
|---|---|---|---|---|
| Superior frontal | 0.176 | 0.167 | 1.000 | 0.366 |
| Medial orbitofrontal | 0.201 | 0.104 | 0.728 | 0.313 |
| Lateral orbitofrontal | 0.019 | 0.890 | 1.000 | 0.891 |
| Rostral middle frontal | 0.355 | **0.007** | **0.049** | **0.043** |
| Rostral anterior cingulate | 0.065 | 0.630 | 1.000 | 0.826 |
| Caudal anterior cingulate | 0.081 | 0.548 | 1.000 | 0.826 |
| Precentral gyrus | 0.362 | **0.005** | **0.035** | **0.029** |

*Note:* Bold values indicate $p < 0.05$.

ratio of two cortical regions in the frontal lobe was associated with neuroticism. This work highlights the utility of using mechanical properties to study age-related changes in the brain, as they reflect the structural integrity of brain tissue and are also associated with behavioral outcomes.

Shear stiffness varied significantly by region and exhibited different relationships with age across the cortex. While several studies have considered effects of age on brain mechanical properties with MRE (Hiscox et al. 2021), we specifically compare our results with those from a study by Arani et al. (2015), which was also focused on an older adult population and reported brain mechanical properties in large lobar regions, making it an appropriate comparator with the current study. Of the cerebral lobes, Arani et al. (2015) reported the strongest age-related softening effect in the temporal lobe (−0.014 kPa/year). In our study, individual regions of the temporal lobe exhibited a range of softening rates from −0.004 kPa/year in the temporal pole (though not statistically significant) to −0.023 kPa/year in the insula. The average softening rate across all temporal regions was −0.014 kPa/year—agreeing with results from Arani et al. (2015) that report the same softening rate in the entire temporal lobe. We found the frontal lobe had regions with the greatest age-related softening ranging to −0.030 kPa/year in the caudal anterior cingulate, which is more than double the softening rate in the frontal lobe reported by Arani et al. (2015) of −0.012 kPa/year. The average softening rate of all frontal cortical regions was also greater at −0.015 kPa/year, suggesting that the high-resolution MRE analysis of individual regions may better resolve cortical mechanical properties by identifying difference between small subregions that would be missed when analyzing the cerebral cortex as a whole. Another recent study reported age-related stiffness differences in 14 cortical regions, which showed stiffness loss in the range of approximately 0.10–0.20 kPa/year across regions that are in consistent with our current study (Pavuluri et al. 2023). When compared to mechanical properties of specific cortical regions in young adults, our results show similar heterogeneity across the lobes (Hiscox et al. 2020).

Similar to previous studies, we did not find significant age-related changes with the other MRE measure, damping ratio. Previous work has shown that damping ratio of the cerebrum did not significantly differ between younger and older adults, even though large scale changes in stiffness were evident (Hiscox et al. 2018). This trend was also identified in earlier work that showed conservation of a related property that quantified the elastic lossy relation of a material (Sack et al. 2011). More recent work has shown some age-related effects on damping ratio in an aging population; however, this was found only in the hippocampus and not in any comparable cortical regions (Delgorio et al. 2021). Physiologically, damping ratio is thought to represent tissue organization and has been linked to actin crosslinking and axonal organization (Guo et al. 2019). Combined, this has led researchers to hypothesize that the relative microstructural organization of the tissue is preserved during age-related degradation in most brain regions.

In comparison to morphometric measures, MRE showed greater sensitivity to age-related structural changes in the cortex. Cortical thickness revealed that only a limited number of regions exhibited significant thinning with advancing age in our sample, including the precentral, superior temporal, and superior parietal regions, compared to nearly all regions exhibiting significant age-related loss in stiffness. Previously established patterns in volumetric analyses show accelerated atrophy in the frontal and temporal cortex of up to −0.5% a year (Fjell, Walhovd, et al. 2009; Lockhart and DeCarli 2014). We find similar rates of cortical thinning (−0.2% to −0.5% compared to cortical thickness at age 75); however, the majority of the significant thinning was found in the parietal lobe. While cortical thinning with age is commonly reported (Fjell, Walhovd, et al. 2009; Lemaitre et al. 2012; Storsve et al. 2014), we note that our sample included just older adults, and it is likely that thinning effects in other regions are only resolvable over a larger age range or in larger samples. Cortical regions where significant thinning was found were mostly confined to the parietal lobe in this study, which exhibited greater softening with MRE in the range of −0.5% up to −1.0%/year (compared to stiffness at age 75). There was little agreement between changes in cortical thickness and stiffness with age. For instance, the superior temporal gyrus exhibited similar −0.46% thinning per year and −0.50% softening per year, while the neighboring middle temporal gyrus exhibited −0.25% and −0.95% thinning and softening per year, respectively. It is also important to note that the MRE measures did not significantly vary with cortical thickness, and different regions were found to be significantly affected by age in stiffness or morphometry, consistent with previous work showing MRE data is not redundant with or biased by regional tissue size (Hiscox et al. 2018, 2021; Takamura et al. 2020).

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Individual differences in personality, specifically neuroticism, were associated with damping ratio in two cortical regions: the precentral gyrus and rostral middle frontal gyrus. These regions contribute to personality formation and emotional regulation, and have been found as structural correlates of personality in prior studies (Levorsen et al. 2023; Mincic 2015; Ormel et al. 2013; Owens et al. 2019; Servaas et al. 2013; Song et al. 2021). Previous work has shown that damping ratio of different regions has been significantly related to individual differences in cognitive function including memory, fluid intelligence, and rule learning (Delgorio et al. 2022; Hiscox, Johnson, McGarry, Schwarb, et al. 2020; Hiscox et al. 2021; Johnson and Telzer 2018; Schwarb et al. 2016, 2019), among others, such that higher damping ratio is associated with poorer task performance. Regions of the cortex where damping ratio was significantly correlated with neuroticism score have been shown to be important for the formation of this trait in previous structural MRI studies that looked at both thickness and surface area measures (Castagna 2019; Song et al. 2021). In addition, volume loss in the dorsolateral prefrontal cortex as a result of a TBI has been linked to increased neuroticism scores (Forbes et al. 2014); notably, the dorsolateral prefrontal cortex encompasses the rostral middle frontal region, and we found the damping ratio of this region to be linked to differences in neuroticism. There are a few hypothesized mechanisms that could explain why the expression of negative traits is linked to poor structural integrity such as higher damping ratio. Namely, personality traits account for predispositions that leads to an influence on brain health or these traits control the response to neuropathological burden leading to unhealthy behaviors (Beck et al. 2024). When considering neuroticism specifically, increased vulnerability to experiencing stress and negative emotions can negatively affect behavior, relationships, and health outcomes, and early behavioral interventions could prevent such negative sequelae (Widiger and Oltmanns 2017). One study has shown that neuroticism is a predictor of telomere length, where individuals with higher neuroticism had shorter telomeres (Van Ockenburg et al. 2014). Short telomeres have separately been shown to be predictive of increased incidence of age-related diseases like Alzheimer's and a biological response to psychological stress (Drury et al. 2011; Epel et al. 2004; Honig et al. 2006), establishing a mechanism for how neuroticism could contribute to accelerated aging and be a predictor for development of dementia (Terracciano et al. 2021). Based on the current study, damping ratio of these cortical regions could be a promising measure to investigate along with neuroticism to understand early structural degradation of the disease and how personality interacts with disease progression.

Many personality findings are hemispheric in nature; however, this study focuses on bilateral associations between mechanical properties and personality measures (Mincic 2015; Wright et al. 2006). In contrast, asymmetry in mechanical properties has not been thoroughly explored, but there is some evidence in subcortical structures that asymmetry contributes to differences in behavioral measures (Hiscox, Johnson, McGarry, Schwarb et al. 2020). In this study, for the two regions where damping ratio was significantly associated with neuroticism, both the left and right sides maintained this association. There were slight difference between effect sizes of the left and right sides, indicating there may be a larger contribution from one hemisphere to this relationship. Furthermore, the bilateral analysis preserved nonsignificant relationships between damping ratio and neuroticism seen on the hemispheric level, indicating that individual hemispheric results were not missed with a bilateral analysis. In future studies, an increased sample size could provide the increased statistical power needed to assess how hemispheric differences between the mechanical properties of cortical regions contributes to personality expression.

While cortical thickness was not linked to neuroticism in this study, it was predictive of conscientiousness in two regions of the frontal cortex: the medial prefrontal cortex and the caudal anterior cingulate. Previous work has shown that conscientiousness was positively associated with cortical thickness in similar regions, especially in the medial orbitofrontal cortex and the dorsomedial prefrontal cortex (Lewis et al. 2018). However, in this study they also investigated the contribution of lifestyle differences in mediating the relationship between personality and brain structure. Notably, the positive association between cortical thickness of frontal regions was attenuated upwards of 30% when accounting for smoking status and allostatic load (characterized by three latent factors reflecting: inflammation, metabolic function, and blood pressure) (Lewis et al. 2018). This finding might suggest a similar predisposition response where differences in personality expression leads to increased allostatic load that can have a long-term impact on brain health. Why the association between cortical structure and conscientiousness was observed based on morphometry but not mechanical properties requires further study, though highlights that morphological and mechanical property measures capture different structural properties that contribute to behavioral outcomes.

Ongoing work in preclinical animal models is being completed to add histological basis to the in vivo measures captured in this study. We have preliminary hypotheses of mechanisms that would influence both the shear stiffness and damping ratio results shown in this study. Shear stiffness captured cross-sectional aging effects. This measure is commonly interpreted to represent tissue composition, including number of cells and cell types (Hiscox et al. 2021). With aging there is identified neuronal cell death, breakdown of supporting glial cells and myelin in the gray matter, and other processes changing the composition of the tissue in each region. This could contribute to the dramatic softening seen in the cortex. Damping ratio has been suggested to be more representative of microstructural organization. During aging, the overarching connections between neurons and regions is preserved. However individual differences such as the number and type of connections between neurons established during formation could lead to different expressions of personality seen in this study. More research in this area is needed to confirm the biological processes that influence mechanical property measures.

This study suggests there is utility in using a regional approach to studying age-related changes in the cortex, that could be obscured if only considering the cortex as a whole or in large regions, potentially masking significant disease- or behavior-related signatures. It also demonstrates the sensitivity of cortical MRE measures to expected neurobiological phenomena, which could be used to increase sensitivity and specificity to disease processes, such as in Alzheimer's disease (Hiscox, Johnson, Mcgarry, Marshall, et al. 2020). We used imaging and inversion approaches we have previously shown to produce reliable mechanical property estimates in the cortex despite its thin, complex geometry and proximity to cerebrospinal fluid. Other cortical MRE approaches have been proposed, including an inversion-recovery based method to suppress CSF signal (Lilaj et al. 2021), and a neural network-based method trained on heterogeneous data (Scott et al. 2022). The latter method has been used to identify differences in dementia etiology based on regional cortical stiffness (Pavuluri et al. 2023). Overall, our results and others point to the feasibility and value of assessing cortical mechanical properties with high-resolution MRE.

This work had several limitations. Notably, the study design was cross-sectional and thus gives a limited view of trends seen during aging; longitudinal studies are needed to confirm the regional aging effects on brain mechanical properties. Longitudinal data could also provide insight on how the relationships between personality and mechanical properties evolve and potentially predict dementia risk. This study was also limited by the overall small sample size, which could further be improved by adding a longitudinal measurement to minimize influence of individual differences in stiffness and increase study power. We have shown through simulations that the MRE imaging and inversion methods used result in reliable cortical mechanical properties, in that they are repeatable, reflect true properties, and are not biased by regional volume (Hiscox, McGarry, and Johnson 2022). However, these methods do not completely recover the true properties, and thus exhibit reduced sensitivity to true biomechanical effects, potentially masking weaker associations between regional mechanical properties with age or personality. In this study, we are still able to resolve associations with neuroticism, but there might be other associations that are masked due to reduced sensitivity. Another limitation of this study was that the overall population was heavily weighted toward women. Sex was controlled for throughout the study, but confirmation of trends should be performed with additional male participants, which would also allow for examination of sex differences in the reported associations.

## 5 | Conclusion

This is the first study to examine the mechanical properties of the cerebral cortex during healthy aging. While the whole cortical mantle softens with age, specific regions of the cortex appear to soften at different rates, suggesting that age-related neurodegeneration is not consistent and some cortical regions experience accelerated stiffness declines. We also examined associations between mechanical properties of cortical regions and personality, including traits of neuroticism and conscientiousness. Higher damping ratio was predictive of greater neuroticism in two cortical regions involved in executive functioning and behavior regulation. Overall, this study provides support for using MRE to study the cortex at a regional level and indicates that MRE has both the sensitivity and specificity needed to study viscoelastic structure–trait relationships.

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**Ethics Statement**

This study was approved by the Institutional Review Board at the University of Delaware.

**Consent**

All study participants provided written informed consent.

**Conflicts of Interest**

The authors declare no conflicts of interest.

**Data Availability Statement**

Numerical data will be made available by simple request. Raw image files will be made available by request which includes a formal project outline and an agreement of data sharing.

**References**

Arani, A., M. C. Murphy, K. J. Glaser, et al. 2015. "Measuring the Effects of Aging and Sex on Regional Brain Stiffness With MR Elastography in Healthy Older Adults." *NeuroImage* 111: 59–64. https://doi.org/10.1016/J.NEUROIMAGE.2015.02.016.

Avinun, R., S. Israel, A. R. Knodt, and A. R. Hariri. 2020. "Little Evidence for Associations Between the Big Five Personality Traits and Variability in Brain Gray or White Matter." *NeuroImage* 220: 117092. https://doi.org/10.1016/J.NEUROIMAGE.2020.117092.

Beck, E. D., T. Yoneda, B. D. James, et al. 2024. "Personality Predictors of Dementia Diagnosis and Neuropathological Burden: An Individual Participant Data Meta-Analysis." *Alzheimer's & Dementia* 20, no. 3: 1497–1514. https://doi.org/10.1002/ALZ.13523.

Bland, J. M., and D. G. Altman. 1995. "Multiple Significance Tests: The Bonferroni Method." *BMJ* 310, no. 6973: 170. https://doi.org/10.1136/BMJ.310.6973.170.

Castagna, P. J. 2019. "Structure Related to Function: Prefrontal Surface Area Has an Indirect Effect on the Relationship Between Amygdala Volume and Trait Neuroticism." *Brain Structure and Function* 224, no. 9: 3309–3320. https://doi.org/10.1007/S00429-019-01974-X/FIGURES/3.

Chen, Y. W., and T. Canli. 2022. ""Nothing to See Here": No Structural Brain Differences as a Function of the Big Five Personality Traits From a Systematic Review and Meta-Analysis." *Personality Neuroscience* 5: e8. https://doi.org/10.1017/PEN.2021.5.

Clarke, D., J. P. Romano, and M. Wolf. 2019. "The Romano-Wolf Multiple Hypothesis Correction in Stata." Accessed August 2, 2024. https://www.iza.org.

Costa, P. T., and R. R. McCrae. 1992. "Normal Personality Assessment in Clinical Practice: The NEO Personality Inventory." *Psychological Assessment* 4, no. 1: 5–13. https://doi.org/10.1037/1040-3590.4.1.5.

Costa, P. T., R. R. McCrae, and C. E. Löckenhoff. 2019. "Personality Across the Life Span." *Annual Review of Psychology* 70: 423–448. https://doi.org/10.1146/ANNUREV-PSYCH-010418-103244/CITE/REFWORKS.

Debast, I., S. P. J. van Alphen, G. Rossi, et al. 2014. "Personality Traits and Personality Disorders in Late Middle and Old Age: Do They Remain Stable?" *A Literature Review. Clinical Gerontologist* 37, no. 3: 253–271. https://doi.org/10.1080/07317115.2014.885917.

Delgorio, P. L., L. V. Hiscox, A. M. Daugherty, et al. 2022. "Structure-Function Dissociations of Human Hippocampal Subfield Stiffness and Memory Performance." *Journal of Neuroscience* 42:

JN-RM-0592-22–JN-RM-0592-7968. https://doi.org/10.1523/JNEUROSCI.0592-22.2022.

Delgorio, P. L., L. V. Hiscox, A. M. Daugherty, et al. 2021. "Effect of Aging on the Viscoelastic Properties of Hippocampal Subfields Assessed With High-Resolution MR Elastography." *Cerebral Cortex* 31, no. 6: 2799–2811. https://doi.org/10.1093/CERCOR/BHAA388.

Delgorio, P. L., L. V. Hiscox, G. McIlvain, et al. 2023. "Hippocampal Subfield Viscoelasticity in Amnestic Mild Cognitive Impairment Evaluated With MR Elastography." *NeuroImage: Clinical* 37: 103327. https://doi.org/10.1016/J.NICL.2023.103327.

Desikan, R. S., F. Ségonne, B. Fischl, et al. 2006. "An Automated Labeling System for Subdividing the Human Cerebral Cortex on MRI Scans Into Gyral Based Regions of Interest." *NeuroImage* 31, no. 3: 968–980. https://doi.org/10.1016/J.NEUROIMAGE.2006.01.021.

Drury, S. S., K. Theall, M. M. Gleason, et al. 2011. "Telomere Length and Early Severe Social Deprivation: Linking Early Adversity and Cellular Aging." *Molecular Psychiatry 2012 17:7* 17, no. 7: 719–727. https://doi.org/10.1038/mp.2011.53.

Epel, E. S., E. H. Blackburn, J. Lin, et al. 2004. "Accelerated Telomere Shortening in Response to Life Stress." *Proceedings of the National Academy of Sciences of the United States of America* 101, no. 49: 17312–17315. https://doi.org/10.1073/PNAS.0407162101/SUPPL_FILE/07162SUPPTEXT.HTML.

Fischl, B. 2012. "FreeSurfer." *NeuroImage* 62, no. 2: 774–781. https://doi.org/10.1016/J.NEUROIMAGE.2012.01.021.

Fjell, A. M., and K. B. Walhovd. 2010. "Structural Brain Changes in Aging: Courses, Causes and Cognitive Consequences." *Reviews in the Neurosciences* 21, no. 3: 187–221. https://doi.org/10.1515/REVNEURO.2010.21.3.187/MACHINEREADABLECITATION/RIS.

Fjell, A. M., K. B. Walhovd, C. Fennema-Notestine, et al. 2009. "One-Year Brain Atrophy Evident in Healthy Aging." *Journal of Neuroscience* 29, no. 48: 15223–15231. https://doi.org/10.1523/JNEUROSCI.3252-09.2009.

Fjell, A. M., L. T. Westlye, I. Amlien, et al. 2009. "High Consistency of Regional Cortical Thinning in Aging Across Multiple Samples." *Cerebral Cortex* 19, no. 9: 2001–2012. https://doi.org/10.1093/CERCOR/BHN232.

Forbes, C. E., J. C. Poore, F. Krueger, A. K. Barbey, J. Solomon, and J. Grafman. 2014. "The Role of Executive Function and the Dorsolateral Prefrontal Cortex in the Expression of Neuroticism and Conscientiousness." *Social Neuroscience* 9, no. 2: 139–151. https://doi.org/10.1080/17470919.2013.871333.

Guo, J., G. Bertalan, D. Meierhofer, et al. 2019. "Brain Maturation Is Associated With Increasing Tissue Stiffness and Decreasing Tissue Fluidity." *Acta Biomaterialia* 99: 433–442. https://doi.org/10.1016/j.actbio.2019.08.036.

Hiscox, L. V. 2018. *Early Characterisation of Neurodegeneration With High-Resolution Magnetic Resonance Elastography.* University of Edinburgh.

Hiscox, L. V., C. L. Johnson, E. Barnhill, et al. 2016. "Magnetic Resonance Elastography (MRE) of the Human Brain: Technique, Findings and Clinical Applications." *Physics in Medicine and Biology* 61, no. 24: R401–R437. https://doi.org/10.1088/0031-9155/61/24/R401.

Hiscox, L. V., C. L. Johnson, M. D. J. McGarry, et al. 2020. "Mechanical Property Alterations Across the Cerebral Cortex due to Alzheimer's Disease. Brain." *Communications* 2, no. 1: fcz049. https://doi.org/10.1093/BRAINCOMMS/FCZ049.

Hiscox, L. V., C. L. Johnson, M. D. J. McGarry, et al. 2018. "High-Resolution Magnetic Resonance Elastography Reveals Differences in Subcortical Gray Matter Viscoelasticity Between Young and Healthy Older Adults." *Neurobiology of Aging* 65: 158–167. https://doi.org/10.1016/J.NEUROBIOLAGING.2018.01.010.

Hiscox, L. V., C. L. Johnson, M. D. J. McGarry, et al. 2020. "Hippocampal Viscoelasticity and Episodic Memory Performance in Healthy Older Adults Examined With Magnetic Resonance Elastography." *Brain Imaging and Behavior* 14, no. 1: 175–185. https://doi.org/10.1007/S11682-018-9988-8/FIGURES/2.

Hiscox, L. V., M. D. J. McGarry, and C. L. Johnson. 2022. "Evaluation of Cerebral Cortex Viscoelastic Property Estimation With Nonlinear Inversion Magnetic Resonance Elastography." *Physics in Medicine and Biology* 67, no. 9: 95002. https://doi.org/10.1088/1361-6560/AC5FDE.

Hiscox, L. V., M. D. J. McGarry, H. Schwarb, et al. 2020. "Standard-Space Atlas of the Viscoelastic Properties of the Human Brain." *Human Brain Mapping* 41, no. 18: 5282–5300. https://doi.org/10.1002/HBM.25192.

Hiscox, L. V., H. Schwarb, M. D. J. McGarry, and C. L. Johnson. 2021. "Aging Brain Mechanics: Progress and Promise of Magnetic Resonance Elastography." *NeuroImage* 232: 117889. https://doi.org/10.1016/J.NEUROIMAGE.2021.117889.

Holm, S. 1979. "A Simple Sequentially Rejective Multiple Test Procedure." *Scandinavian Journal of Statistics* 6, no. 2: 65–70.

Honig, L. S., N. Schupf, J. H. Lee, M. X. Tang, and R. Mayeux. 2006. "Shorter Telomeres Are Associated With Mortality in Those With APOE ϵ4 and Dementia." *Annals of Neurology* 60, no. 2: 181–187. https://doi.org/10.1002/ANA.20894.

Jenkinson, M., P. Bannister, M. Brady, and S. Smith. 2002. "Improved Optimization for the Robust and Accurate Linear Registration and Motion Correction of Brain Images." *NeuroImage* 17, no. 2: 825–841. https://doi.org/10.1006/NIMG.2002.1132.

Jenkinson, M., C. F. Beckmann, T. E. J. Behrens, M. W. Woolrich, and S. M. Smith. 2012. "FSL." *NeuroImage* 62, no. 2: 782–790. https://doi.org/10.1016/J.NEUROIMAGE.2011.09.015.

Johnson, C. L., J. L. Holtrop, A. T. Anderson, and B. P. Sutton. 2016. "Brain MR Elastography With Multiband Excitation and Nonlinear Motion-Induced Phase Error Correction." In *Proceedings of the International Society for Magnetic Resonance in Medicine*. ISMRM.

Johnson, C. L., H. Schwarb, K. M. Horecka, et al. 2018. "Double Dissociation of Structure-Function Relationships in Memory and Fluid Intelligence Observed With Magnetic Resonance Elastography." *NeuroImage* 171: 99–106. https://doi.org/10.1016/J.NEUROIMAGE.2018.01.007.

Johnson, C. L., H. Schwarb, M. D. J. McGarry, et al. 2016. "Viscoelasticity of Subcortical Gray Matter Structures." *Human Brain Mapping* 37, no. 12: 4221–4233. https://doi.org/10.1002/HBM.23314.

Johnson, C. L., and E. H. Telzer. 2018. "Magnetic Resonance Elastography for Examining Developmental Changes in the Mechanical Properties of the Brain." *Developmental Cognitive Neuroscience* 33: 176–181. https://doi.org/10.1016/J.DCN.2017.08.010.

Lai, H., S. Wang, Y. Zhao, L. Zhang, C. Yang, and Q. Gong. 2019. "Brain Gray Matter Correlates of Extraversion: A Systematic Review and Meta-Analysis of Voxel-Based Morphometry Studies." *Human Brain Mapping* 40, no. 14: 4038–4057. https://doi.org/10.1002/HBM.24684.

Lemaitre, H., A. L. Goldman, F. Sambataro, et al. 2012. "Normal Age-Related Brain Morphometric Changes: Nonuniformity Across Cortical Thickness, Surface Area and Gray Matter Volume?" *Neurobiology of Aging* 33, no. 3: 617.e1–617.e9. https://doi.org/10.1016/J.NEUROBIOLAGING.2010.07.013.

Levorsen, M., R. Aoki, K. Matsumoto, C. Sedikides, and K. Izuma. 2023. "The Self-Concept Is Represented in the Medial Prefrontal Cortex in Terms of Self-Importance." *Journal of Neuroscience: The Official Journal of the Society for Neuroscience* 43, no. 20: 3675–3686. https://doi.org/10.1523/JNEUROSCI.2178-22.2023.

Lewis, G. J., D. A. Dickie, S. R. Cox, et al. 2018. "Widespread Associations Between Trait Conscientiousness and Thickness of Brain Cortical Regions." *NeuroImage* 176: 22–28. https://doi.org/10.1016/J.NEUROIMAGE.2018.04.033.

Lilaj, L., H. Herthum, T. Meyer, et al. 2021. "Inversion-Recovery MR Elastography of the Human Brain for Improved Stiffness Quantification Near Fluid–Solid Boundaries." *Magnetic Resonance in Medicine* 86, no. 5: 2552–2561. https://doi.org/10.1002/MRM.28898.

Lockhart, S. N., and C. DeCarli. 2014. "Structural Imaging Measures of Brain Aging." *Neuropsychology Review* 24, no. 3: 271–289. https://doi.org/10.1007/S11065-014-9268-3/FIGURES/8.

Manduca, A., T. E. Oliphant, M. A. Dresner, et al. 2001. "Magnetic Resonance Elastography: Non-invasive Mapping of Tissue Elasticity." *Medical Image Analysis* 5, no. 4: 237–254. https://doi.org/10.1016/S1361-8415(00)00039-6.

Manduca, A., P. V. Bayly, R. L. Ehman, et al. 2021. "MR Elastography: Principles, Guidelines, and Terminology." *Magnetic Resonance in Medicine* 85, no. 5: 2377–2390. https://doi.org/10.1002/MRM.28627.

McGarry, M. D. J., E. E. W. V. Houten, C. L. Johnson, et al. 2012. "Multiresolution MR Elastography Using Nonlinear Inversion." *Medical Physics* 39, no. 10: 6388–6396. https://doi.org/10.1118/1.4754649.

McGarry, M. D. J., E. E. W. V. Houten, P. R. Perriñez, A. J. Pattison, J. B. Weaver, and K. D. Paulsen. 2011. "An Octahedral Shear Strain-Based Measure of SNR for 3D MR Elastography." *Physics in Medicine & Biology* 56, no. 13: N153–N164. https://doi.org/10.1088/0031-9155/56/13/N02.

McIlvain, G., R. G. Clements, E. M. Magoon, J. M. Spielberg, E. H. Telzer, and C. L. Johnson. 2020. "Viscoelasticity of Reward and Control Systems in Adolescent Risk Taking." *NeuroImage* 215: 116850. https://doi.org/10.1016/J.NEUROIMAGE.2020.116850.

McIlvain, G., J. M. Schneider, M. A. Matyi, et al. 2022. "Mapping Brain Mechanical Property Maturation From Childhood to Adulthood." *NeuroImage* 263: 119590. https://doi.org/10.1016/J.NEUROIMAGE.2022.119590.

Mincic, A. M. 2015. "Neuroanatomical Correlates of Negative Emotionality-Related Traits: A Systematic Review and Meta-Analysis." *Neuropsychologia* 77: 97–118. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2015.08.007.

Mouton, P. R., L. J. Martin, M. E. Calhoun, G. Dal Forno, and D. L. Price. 1998. "Cognitive Decline Strongly Correlates With Cortical Atrophy in Alzheimer's Dementia." *Neurobiology of Aging* 19, no. 5: 371–377. https://doi.org/10.1016/S0197-4580(98)00080-3.

Munder, T., A. Pfeffer, S. Schreyer, et al. 2018. "MR Elastography Detection of Early Viscoelastic Response of the Murine Hippocampus to Amyloid β Accumulation and Neuronal Cell Loss due to Alzheimer's Disease." *Journal of Magnetic Resonance Imaging* 47, no. 1: 105–114. https://doi.org/10.1002/jmri.25741.

Murphy, M. C., J. Huston, C. R. Jack, et al. 2011. "Decreased Brain Stiffness in Alzheimer's Disease Determined by Magnetic Resonance Elastography." *Journal of Magnetic Resonance Imaging* 34, no. 3: 494–498. https://doi.org/10.1002/JMRI.22707.

Murphy, M. C., D. T. Jones, C. R. Jack, et al. 2016. "Regional Brain Stiffness Changes Across the Alzheimer's Disease Spectrum." *NeuroImage: Clinical* 10: 283–290. https://doi.org/10.1016/J.NICL.2015.12.007.

Muthupillai, R., D. J. Lomas, P. J. Rossman, J. F. Greenleaf, A. Manduca, and R. L. Ehman. 1995. "Magnetic Resonance Elastography by Direct Visualization of Propagating Acoustic Strain Waves." *Science* 269, no. 5232: 1854–1857. https://doi.org/10.1126/SCIENCE.7569924.

Ormel, J., A. Bastiaansen, H. Riese, et al. 2013. "The Biological and Psychological Basis of Neuroticism: Current Status and Future Directions." *Neuroscience & Biobehavioral Reviews* 37, no. 1: 59–72. https://doi.org/10.1016/J.NEUBIOREV.2012.09.004.

Owens, M. M., C. S. Hyatt, J. C. Gray, et al. 2019. "Cortical Morphometry of the Five-Factor Model of Personality: Findings From the Human Connectome Project Full Sample." *Social Cognitive and Affective Neuroscience* 14, no. 4: 381–395. https://doi.org/10.1093/SCAN/NSZ017.

Pavuluri, K. D., J. Huston, R. L. Ehman, et al. 2024. "Associations Between Vascular Health, Brain Stiffness and Global Cognitive Function." *Brain Communications* 6, no. 2: fcae073. https://doi.org/10.1093/BRAINCOMMS/FCAE073.

Pavuluri, K. D., J. M. Scott, J. Huston, et al. 2023. "Differential Effect of Dementia Etiology on Cortical Stiffness as Assessed by MR Elastography." *NeuroImage: Clinical* 37: 103328. https://doi.org/10.1016/J.NICL.2023.103328.

Pini, L., M. Pievani, M. Bocchetta, et al. 2016. "Brain Atrophy in Alzheimer's Disease and Aging." *Ageing Research Reviews* 30: 25–48. https://doi.org/10.1016/J.ARR.2016.01.002.

Riccelli, R., N. Toschi, S. Nigro, A. Terracciano, and L. Passamonti. 2017. "Surface-Based Morphometry Reveals the Neuroanatomical Basis of the Five-Factor Model of Personality." *Social Cognitive and Affective Neuroscience* 12, no. 4: 671–684. https://doi.org/10.1093/SCAN/NSW175.

Roberts, B. W., and W. F. DelVecchio. 2000. "The Rank-Order Consistency of Personality Traits From Childhood to Old Age: A Quantitative Review of Longitudinal Studies." *Psychological Bulletin* 126, no. 1: 3–25. https://doi.org/10.1037/0033-2909.126.1.3.

Sack, I., B. Beierbach, J. Wuerfel, et al. 2009. "The Impact of Aging and Gender on Brain Viscoelasticity." *NeuroImage* 46, no. 3: 652–657. https://doi.org/10.1016/J.NEUROIMAGE.2009.02.040.

Sack, I., K. Jöhrens, J. Würfel, and J. Braun. 2013. "Structure-Sensitive Elastography: On the Viscoelastic Powerlaw Behavior of In Vivo Human Tissue in Health and Disease." *Soft Matter* 9, no. 24: 5672–5680. https://doi.org/10.1039/c3sm50552a.

Sack, I., K. J. Streitberger, D. Krefting, F. Paul, and J. Braun. 2011. "The Influence of Physiological Aging and Atrophy on Brain Viscoelastic Properties in Humans." *PLoS One* 6, no. 9: e23451. https://doi.org/10.1371/JOURNAL.PONE.0023451.

Scholtens, L. H., S. C. de Lange, and M. P. van den Heuvel. 2021. "Simple Brain Plot." Zenodo. https://zenodo.org/records/5346593.

Schregel, K., E. W. Née Tysiak, P. Garteiser, et al. 2012. "Demyelination Reduces Brain Parenchymal Stiffness Quantified In Vivo by Magnetic Resonance Elastography." *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 17: 6650–6655. https://doi.org/10.1073/PNAS.1200151109/SUPPL_FILE/PNAS.201200151SI.PDF.

Schwarb, H., C. L. Johnson, A. M. Daugherty, et al. 2017. "Aerobic Fitness, Hippocampal Viscoelasticity, and Relational Memory Performance." *NeuroImage* 153: 179–188. https://doi.org/10.1016/J.NEUROIMAGE.2017.03.061.

Schwarb, H., C. L. Johnson, M. R. Dulas, et al. 2019. "Structural and Functional MRI Evidence for Distinct Medial Temporal and Prefrontal Roles in Context-Dependent Relational Memory." *Journal of Cognitive Neuroscience* 31, no. 12: 1857–1872. https://doi.org/10.1162/JOCN_A_01454.

Schwarb, H., C. L. Johnson, M. D. J. McGarry, and N. J. Cohen. 2016. "Medial Temporal Lobe Viscoelasticity and Relational Memory Performance." *NeuroImage* 132: 534–541. https://doi.org/10.1016/J.NEUROIMAGE.2016.02.059.

Scott, J. M., K. D. Pavuluri, J. D. Trzasko, et al. 2022. "Impact of Material Homogeneity Assumption on Cortical Stiffness Estimates by MR Elastography." *Magnetic Resonance in Medicine* 88, no. 2: 916–929. https://doi.org/10.1002/MRM.29226.

Segerstrom, S. C. 2020. "Personality and Incident Alzheimer's Disease: Theory, Evidence, and Future Directions." *Journals of Gerontology: Series B* 75, no. 3: 513–521. https://doi.org/10.1093/GERONB/GBY063.

Servaas, M. N., J. van der Velde, S. G. Costafreda, et al. 2013. "Neuroticism and the Brain: A Quantitative Meta-Analysis of Neuroimaging Studies Investigating Emotion Processing." *Neuroscience & Biobehavioral*

*Reviews* 37, no. 8: 1518–1529. https://doi.org/10.1016/J.NEUBIOREV.2013.05.005.

Song, L., Z. Zhou, J. Meng, et al. 2021. "Rostral Middle Frontal Gyrus Thickness Mediates the Relationship Between Genetic Risk and Neuroticism Trait." *Psychophysiology* 58, no. 2: e13728. https://doi.org/10.1111/PSYP.13728.

Steiger, J. H. 1980. "Tests for Comparing Elements of a Correlation Matrix." *Psychological Bulletin* 87, no. 2: 245–251. https://doi.org/10.1037/0033-2909.87.2.245.

Storsve, A. B., A. M. Fjell, C. K. Tamnes, et al. 2014. "Differential Longitudinal Changes in Cortical Thickness, Surface Area and Volume Across the Adult Life Span: Regions of Accelerating and Decelerating Change." *Journal of Neuroscience* 34, no. 25: 8488–8498. https://doi.org/10.1523/JNEUROSCI.0391-14.2014.

Sutin, A. R., M. Luchetti, D. Aschwanden, et al. 2023. "Five-Factor Model Personality Domains and Facets Associated With Markers of Cognitive Health." *Journal of Individual Differences* 44, no. 2: 97–108. https://doi.org/10.1027/1614-0001/A000383.

Takamura, T., U. Motosugi, Y. Sasaki, et al. 2020. "Influence of Age on Global and Regional Brain Stiffness in Young and Middle-Aged Adults." *Journal of Magnetic Resonance Imaging* 51, no. 3: 727–733. https://doi.org/10.1002/JMRI.26881.

Terracciano, A., D. Aschwanden, L. Passamonti, et al. 2021. "Is Neuroticism Differentially Associated With Risk of Alzheimer's Disease, Vascular Dementia, and Frontotemporal Dementia?" *Journal of Psychiatric Research* 138: 34–40. https://doi.org/10.1016/J.JPSYCHIRES.2021.03.039.

Terracciano, A., P. T. Costa, and R. R. McCrae. 2006. "Personality Plasticity After Age 30." *Alzheimer's & Dementia* 32, no. 8: 999–1009. https://doi.org/10.1177/0146167206288599.

Terracciano, A., A. R. Sutin, Y. An, et al. 2014. "Personality and Risk of Alzheimer's Disease: New Data and Meta-Analysis." *Personality and Social Psychology Bulletin* 10, no. 2: 179–186. https://doi.org/10.1016/J.JALZ.2013.03.002.

Van Ockenburg, S. L., P. De Jonge, P. Van Der Harst, J. Ormel, and J. G. M. Rosmalen. 2014. "Does Neuroticism Make You Old? Prospective Associations Between Neuroticism and Leukocyte Telomere Length." *Psychological Medicine* 44, no. 4: 723–729. https://doi.org/10.1017/S0033291713001657.

Widiger, T. A., and J. R. Oltmanns. 2017. "Neuroticism Is a Fundamental Domain of Personality With Enormous Public Health Implications." *World Psychiatry* 16, no. 2: 144–145. https://doi.org/10.1002/WPS.20411.

Wilson, R. S., E. Segawa, P. A. Boyle, S. E. Anagnos, L. P. Hizel, and D. A. Bennett. 2012. "The Natural History of Cognitive Decline in Alzheimer's Disease." *Psychology and Aging* 27, no. 4: 1008–1017. https://doi.org/10.1037/A0029857.

Wright, C. I., D. Williams, E. Feczko, et al. 2006. "Neuroanatomical Correlates of Extraversion and Neuroticism." *Cerebral Cortex* 16, no. 12: 1809–1819. https://doi.org/10.1093/CERCOR/BHJ118.

## Supporting Information

Additional supporting information can be found online in the Supporting Information section.