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Bilingualism modulates baseline brain–cognition relationships in aging: Evidence from the HABS-HD cohort

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ABSTRACT

Bilingualism has been proposed to confer advantages in cognitive aging, yet the neural mechanisms underlying any such advantages remain debated. In a pre-registered analysis of cross-sectional and longitudinal data from elders in the HABS-HD cohort, we asked whether bilingualism is associated with three measures of brain structure (total brain volume, hippocampal volume and white-matter lesions) and/or moderates the relationship between brain structure and two measures of cognition (executive function and episodic memory). Overall, we found no significant differences between bilinguals and monolinguals in their baseline brain structure or subsequent change in brain structure, suggesting that a life of bilingualism was not clearly associated with Brain Reserve or Brain Maintenance in old age. In baseline analyses, bilingualism moderated the relationship between total brain volume and executive function, and between hippocampal volume and episodic memory, such that these cognitive functions were less dependent on these brain measures in bilinguals, consistent with the concept of Cognitive Reserve. However, any effect of bilingualism on longitudinal associations between brain-change slopes and cognitive-change slopes did not reach significance, suggesting that bilingualism-related Cognitive Reserve may be limited to baseline differences. Further, exploratory analyses showed that the effects of bilingualism on hippocampal volume, and on its relationship with episodic memory, might differ according to clinical dementia status. In summary, our findings suggest that bilingualism is associated with altered baseline brain–cognition relationships, rather than with preservation of brain structure.

1. Introduction

Cognitive aging is characterized by substantial individual variability (Bettcher et al., 2019; Persson et al., 2016; Stern et al., 2019). While advancing age is typically accompanied by structural brain changes, including cortical atrophy, hippocampal shrinkage and increasing white matter lesions, the cognitive consequences of these changes vary markedly across individuals (Belleville et al., 2021; Mungas et al., 2018; Persson et al., 2016). While some older adults exhibit pronounced decline, others maintain relatively preserved cognitive function despite comparable or even greater neuropathological burden (Bettcher et al., 2019; Solé-Padullés et al., 2009; Stern et al., 2019). Understanding the mechanisms that enable this "Cognitive Reserve" - i.e., apparent dissociation between brain health and cognitive outcomes - remains a central challenge in cognitive neuroscience and aging research (Aron et al., 2022; Belleville et al., 2021; Henson, 2026), with important implications for identifying potential factors that enhance resilience to neurodegeneration and promote healthy cognitive aging.

Indeed, several developmental, experiential and lifestyle factors have been claimed to support cognition in later life, such as education, occupational complexity and social engagement (Lee et al., 2025; Mungas et al., 2018; Scarmeas and Stern, 2003; Zahodne et al., 2019). Bilingualism has also emerged as a potential candidate, because it represents a sustained, cognitively-demanding experience that requires

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continuous monitoring, selection and inhibition of competing linguistic systems, engaging domain-general executive control processes (Bialystok, 2017; Bialystok, 2021). Unlike many other cognitively-demanding activities, bilingualism is typically sustained across decades and embedded in everyday communication (Gallo et al., 2022). Although bilingualism may be associated with socioeconomic and contextual factors, including immigration history, nativity, education, and acculturation, it represents a form of everyday cognitive experience that is conceptually distinct from formal education or socioeconomic status (Arce Rentería et al., 2026; Rumbaut & Massey, 2013). This makes bilingualism a potentially important, but context-dependent, candidate for understanding cognitive resilience across diverse populations (Bialystok, 2017). Clinically, several prospective studies have reported that bilingual individuals experience a delay of approximately four to five years in the onset of dementia symptoms compared to monolinguals, even when matched for education and other demographic factors (Alladi et al., 2017; Bialystok et al., 2007; Craik et al., 2010; Gold, 2016; Mukadam et al., 2017; Van den Noort et al., 2019; Voits, Pliatsikas, et al., 2020). A substantial body of behavioural research has claimed that bilingualism confers cognitive advantages across the lifespan, particularly in executive function and episodic memory (Antoniou, 2019; Bialystok et al., 2012; Grundy and Timmer, 2017; Grundy, 2020; Privitera and Weekes, 2023). However, this claim remains debated, with findings varying considerably across studies and meta-analyses, and with several studies highlighting methodological problems in the bilingual advantage literature (Lehtonen et al., 2018; Masullo et al., 2024; Paap et al., 2015). Importantly, it remains unclear whether any such cognitive advantages owing to bilingualism arise from better development or maintenance of brain structure, or from some form of functional compensation that maintains people's cognitive abilities despite normal age-related brain decline.

Contemporary theoretical frameworks have proposed consensus definitions and analytic guidelines for investigating mechanisms of resilience in aging (Stern et al., 2023). One explanation is Brain Reserve, which reflects the amount of neurobiological capital available to an individual, such as total brain volume (e.g. total number of neurons). According to the Brain Reserve hypothesis, a larger overall brain volume acts as a passive buffer, increasing the threshold of damage required to trigger clinical impairment (Bartrés-Faz and Arenaza-Urquijo, 2011; Stern et al., 2023). In the present context, we restrict these brain properties to those structural measures available from a T1-weighted MRI scan, and assume that an earlier lifetime of bilingualism can affect these structural properties when measured in old age. We therefore test the Brain Reserve hypothesis by examining baseline differences between bilinguals and monolinguals, i.e., for the first time-point measured in the HABS-HD cohort of elders.

As second possible explanation is Brain Maintenance, which emphasizes instead reduced age-related neural deterioration in later life (Nyberg et al., 2012). Unlike the passive buffering of reserve, this hypothesis posits that lifestyle factors, such as the continuous demand of managing two languages, may counteract age-related brain loss through experience-dependent plasticity (Abutalebi et al., 2015; Costumero et al., 2020a; Pliatsikas et al., 2020). Within the present context, we test this hypothesis by comparing the rate of change of structural brain measures, which might differ between bilinguals and monolinguals, even if their baseline values when entering later life (i.e., Brain Reserves) are equivalent.

Finally, a third possible explanation is Cognitive Reserve, which refers to the capacity to maintain cognitive performance despite structural brain decline, for example through more flexible, efficient, or compensatory recruitment of functional networks (Stern et al., 2023). Cognitive Reserve is often implicated by moderation analyses, i.e., tests of whether bilingualism reduces the dependency of cognitive performance on age, or the dependency of cognitive performance on brain structure (Borsa et al., 2018; Elliott et al., 2025a; Estanga et al., 2017; Stevens et al., 2023). In the present context, this corresponds to a significant interaction between bilingualism and brain structure in the prediction of cognitive ability: If a lifetime of bilingualism increases Cognitive Reserve, then the cognitive ability of bilinguals should be less strongly related to their brain structure, either at baseline, or in terms of longitudinal change.

Previous neuroimaging studies have addressed the Brain Reserve hypothesis, and reported that bilingualism is associated with experience-dependent gray-matter increases in cortical and subcortical regions supporting language control, executive function and memory (Abutalebi and Green, 2007; Torres et al., 2022). In late life for example, bilinguals have been claimed to possess greater gray-matter volume in key executive control regions, including the anterior cingulate cortex and inferior parietal lobule, than do monolinguals (Abutalebi et al., 2015; Abutalebi et al., 2015; Heim et al., 2019), as well as in hippocampus (Voits et al., 2020; Voits et al., 2022; Voits et al., 2024). At present, however, little is known about how these associations between bilingualism and brain structural relate to neurodegenerative disease that is common in old age, i.e., clinical diagnoses of dementia. Independent of bilingualism, extensive research on Alzheimer's disease demonstrates that the associations among brain structure, neuropathology and cognition vary across stages of disease progression (Archer et al., 2011; Planche et al., 2022; Solé-Padullés et al., 2009). For example, higher Cognitive Reserve is associated with slower cognitive decline prior to a dementia diagnosis, but faster decline after the diagnosis (Soldan et al., 2017). One explanation for this is that Cognitive Reserve can compensate for neurodegenerative processes to a certain extent (i.e., for a certain period of time early in a disease like Alzheimer's), but eventually the compensation fails, such that a clinical diagnosis is given, by which time these individuals have progressed further in the disease than those with less Cognitive Reserve. Indeed, while some large-scale studies did not find a difference in dementia incidence according to bilingual status (Mukadam et al., 2018; Yeung et al., 2014; Zahodne et al., 2014), one study did find faster conversion from the stage of Mild Cognitive Impairment (MCI) to probable Alzheimer's Disease once clinical thresholds are reached, consistent with Cognitive Reserve (Berkes et al., 2020). While these large-scale studies did not incorporate neuroimaging data, limiting their ability to examine how bilingual experience relates to brain structure across disease progression, they highlight the need to explicitly account for clinical diagnosis.

In this context, most studies with neuroimaging data have used cross-sectional designs, which can only provide indirect support for reserve versus maintenance, since they cannot disentangle change from pre-existing individual differences (Walhovd et al., 2023). Testing whether bilingualism is associated with better Brain Maintenance, or slower neurodegenerative trajectories, requires longitudinal designs with repeated neuroimaging and cognitive assessments. There are some intervention studies that suggest that bilingualism and second-language training produce measurable neural plasticity. For example, short- to medium-term language training in healthy adults has been reported to increase cortical and hippocampal volume, as well as microstructural changes in white-matter pathways, consistent with experience-dependent myelination (Mårtensson et al., 2012; Schlegel et al., 2012; Stein et al., 2012; Van de Putte et al., 2018. However, such effects could be transient (Hosoda et al., 2013), meaning that their relevance for cognitive aging and dementia remains unclear. In the few naturalistic longitudinal studies performed to date, bilingual experience has been associated with reduced decline of subcortical, cerebellar and hippocampal volumes during normal aging and early transition to MCI (Costumero et al., 2020; Peitz et al., 2023; Torres et al., 2022). However, these studies are limited by relatively small sample sizes, which reduces statistical power and may contribute to the variability in reported effects, as well as heterogeneous definitions of bilingualism, limited control for baseline brain integrity and short follow-up periods (Del Maschio et al., 2021).

The HABS-HD cohort is rare in having a large sample (1000s of

participants) with longitudinal neuroimaging and cognitive data. In previous work on this cohort, we showed that bilingualism is associated with superior baseline executive function and episodic memory, as well as slower longitudinal decline in episodic memory in older adults (Xia et al., 2026). Here we build on this by examining the potential neural correlates of this bilingual advantage. More specifically, we pre-registered (https://osf.io/dxrqz/files/aqgc5) a number of hypotheses restricted to three different brain measures (to reduce the multiple comparison problem): 1) total brain volume (TBV), 2) hippocampal volume (HV), and 3) white matter lesions (WML). TBV, when adjusted for head-size (total intracranial volume, TIV), shows clear decline with adult age and correlates with general cognitive performance (Fürtjes et al., 2025). HV is also known to decline with age, accelerating after middle-age (Nobis et al., 2019), and correlates with episodic memory in some individuals, though the evidence is mixed (Vidal-Pineiro et al., 2025). Notably, the hippocampus-memory association is stronger in individuals who are at risk for Alzheimer's disease than their control counterparts (Gorbach et al., 2020). WMLs in healthy people only really emerge from middle-age, and also show modest correlations with general cognitive performance (d'Arbeloff et al., 2019).

For each brain measure, our pre-registered hypotheses tested whether bilingualism had a direct effect on any of the above brain measures, either at baseline (as predicted by Brain Reserve) or in terms of subsequent change (as predicted by Brain Maintenance), and/or whether it moderated the relationship between that brain measure and cognition (as predicted by Cognitive Reserve). Given the above evidence that the effect of factors linked to Cognitive Reserve may differ with versus without the presence of a neurodegenerative disease, we also performed exploratory analysis (not pre-registered) to see if any of the above tests varied with diagnosis of MCI/dementia, by adding a further grouping of participants according to whether they received such a diagnosis at any point during the HABS-HD study (Converters), or whether they did not (Stable). Figure 1 demonstrates the theoretical framework and the hypothesized bilingual effects.

2. Methods

2.1. Participants and data selection

Data were obtained from the Health and Aging Brain Study—Health Disparities (HABS-HD) Wave 7 release, a longitudinal study conducted at the University of North Texas Health Science Center (UNTHSC). The cohort recruited racially and ethnically diverse older adults from the Dallas–Fort Worth area in order to study disparities in Alzheimer's disease and related dementias (ADRD). Detailed information about participant characteristics and methods can be found in Petersen et al. (2025).

The present cross-sectional analysis included 3655 participants at baseline who had complete data for MRI measures (TBV, TIV, HV and WML), bilingualism status, gender, age and education. For the cross-sectional brain–cognition analyses, baseline MRI and cognitive assessments were required to occur within 0.5 years of each other. The time difference between baseline brain and cognitive assessments had a minimum of −0.986 years, median of 0.02 years and maximum of 1.032 years (see Figure S2 in Supplementary Material). To ensure that both assessments were conducted within a close timeframe, we applied a cut-off of 0.5 years. Using this criterion, 4 participants whose assessments exceeded this interval were excluded from the analysis of the modulating effects of bilingualism on the relationship between brain and cognition. For longitudinal analyses, the sample consisted of 1471 participants with complete data for at least two MRI visits. Participants contributed between 2 and 4 longitudinal MRI timepoints, with scans occurring at approximately two-year intervals and total follow-up spanning approximately 2–6 years. Cognitive and MRI assessments were not always collected at identical timepoints. Therefore, for the longitudinal brain–cognition analyses, participant-specific slopes were estimated separately for MRI measures and cognitive measures using the available longitudinal observations. The distribution of maximum visit number by bilingualism group is reported in Table S9.

2.2. Bilingualism status

Consistent with prior HABS-HD investigations (Grasso et al., 2023; Petersen et al., 2022), participants were classified as bilingual versus monolingual based on their self-reported response to the question: "Do you speak a secondary language?". Testing was conducted in English or Spanish according to participant preference. As HABS-HD does not systematically assess the number of additional languages spoken, this classification reflects the presence of at least one additional language rather than a strict distinction between bilingual and multilingual speakers. Also, due to the largely missing data (i.e., 98.8%) on second language (L2) history (i.e., age of L2 acquisition, L2 usage, and L2 proficiency), theses variables were not analysed. As partial characterization of language background, we examined the Short Acculturation Scale for Hispanics (SASH) language-use score,[1] where 1 indicates exclusive Spanish use, 3 indicates balanced Spanish–English use, and 5 indicates exclusive English use. Hispanic bilinguals reported more balanced Spanish–English use than Hispanic monolinguals, whereas White and Black bilinguals were largely English-dominant. These differences suggest that the bilingualism variable did not capture equivalent language-use profiles across ethnic groups, which further supports the importance of the Hispanic-only sensitivity analyses (see Section 3 in Supplementary Materials). These analyses allowed us to examine bilingualism-related effects within the subgroup in which Spanish–English/English-Spanish bilingualism was most clearly represented, while reducing heterogeneity in language background. The SASH language-use measure and its relevance to characterizing language background in this cohort are discussed in more detail in our previous paper (Xia et al., 2026).

2.3. Brain measures

All brain measures were derived from longitudinal FreeSurfer (v.7.3.2) applied to T1-weighted images (https://apps.unthsc.edu/itr/our). We focused on three primary neuroanatomical markers: 1) Total Brain Volume (TBV); 2) Hippocampal Volume (HV; sum of left and right Hippocampus volume); 3) White Matter Lesions (WML). Total Intracranial Volume (TIV) was used as a covariate to adjust for head size in all models predicting brain measures. To maximize sample size, WMLs were defined as hypo-intense voxels on the T1-weighted images, because T2-weighted images (for defining white-matter hyper-intensities) were unavailable or of variable quality for many participants. White-matter hypo-intensities on T1-weighted images have been shown to correspond closely with hyper-intensities on T2-weighted images, and exhibit comparable associations with age, vascular risk factors and cognitive outcomes (Wei et al., 2019). Because of their positive skew, WMLs were log-transformed.

The HABS-HD data used here came from two scanners: a Siemens Skyra and a Siemens Vida1 (see Figure S2 in Supplementary material). To account for potential scanner-related variability, we applied ComBat harmonization using the longCombat implementation (Beer et al., 2020; https://github.com/jcbeer/longCombat). ComBat estimates an offset and a scaling parameter for each scanner, using an empirical Bayesian approach, having adjusted for (non-MRI) covariates of interest, which in our case were bilingualism, ethnicity, gender, age, age^2 and education (see statistical models below).

[1] The SASH language-use score was calculated by averaging five items assessing language use across different contexts: general reading and speaking language, language used as a child, language usually spoken at home, language usually used for thinking, and language usually spoken with friends.

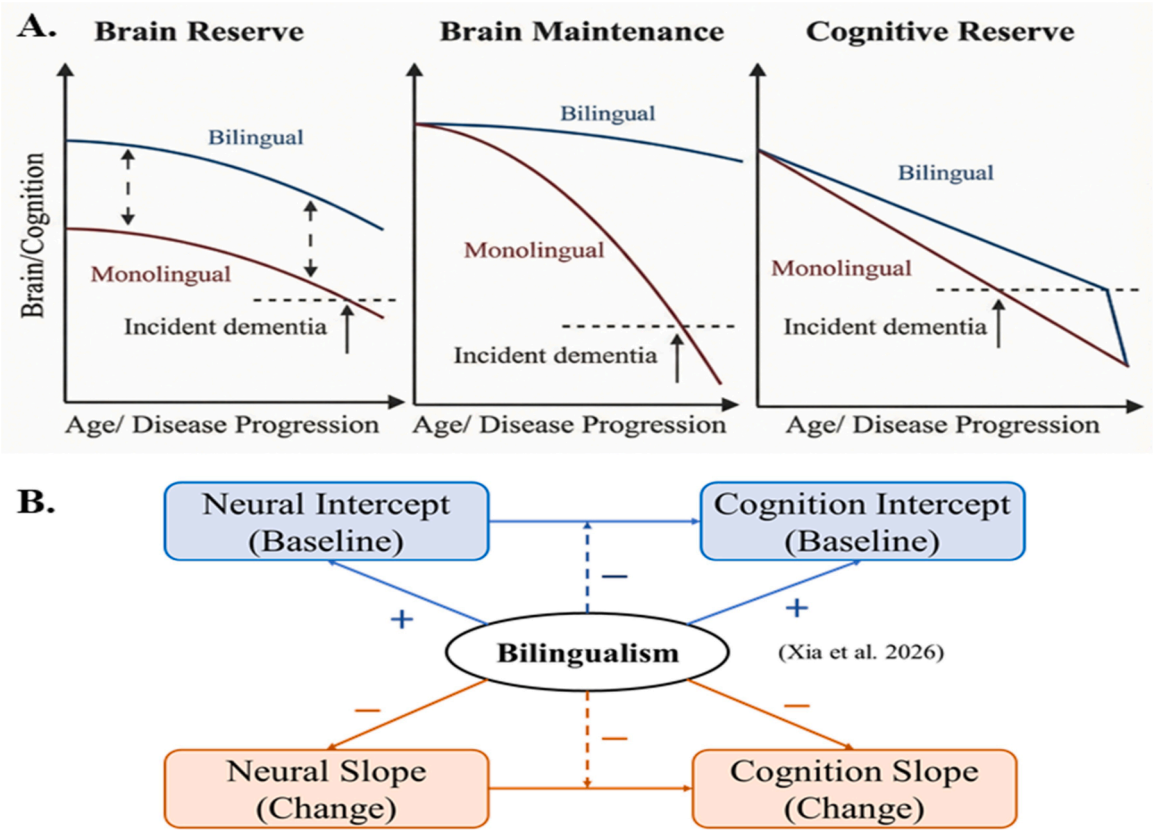

Fig. 1. Theoretical frameworks of Brain Reserve, Brain Maintenance and Cognitive Reserve, and hypothesized bilingualism effects across cognitive status. A) Conceptual illustration of Brain Reserve (left), Brain Maintenance (middle), and Cognitive Reserve (right) models. The y-axis represents either cognitive performance or brain integrity across age and disease progression. In the Brain Reserve model, Bilinguals exhibit higher baseline levels (intercept) with a rate of decline parallel to monolinguals. In the Brain Maintenance model, Bilingualism attenuates age-related neurodegeneration, resulting in a slower rate of structural decline (shallower slope). In the Cognitive Reserve model, bilinguals maintain cognitive performance despite increasing pathology, resulting in delayed clinical onset, followed by potentially steeper decline after the clinical threshold is reached. Horizontal dashed lines indicate the clinical threshold for dementia. B) Hypothesized pathways of bilingualism on neural and cognitive outcomes. Bilingualism may influence baseline levels (intercepts) and rates of change (slopes) in neural structure and cognitive performance. Solid pathways indicate direct associations; dashed pathways indicate moderation of the brain–cognition relationship (cognitive reserve). Plus (+) and minus (–) symbols denote positive associations with higher baseline levels and slower rates of decline, respectively. Cognitive outcomes are reported in Xia et al. (2026).

2.4. Cognitive measures

We utilized two composite factor scores, Executive Function and Episodic Memory, derived from the factor analysis of a comprehensive neuropsychological battery that was performed in our previous study (Xia et al., 2026). The battery included the Trail Making Test (Parts A and B), Digit Span (forward/backward), Digit Symbol Substitution, Logical Memory (I and II), Total Learning and Delayed Recall from the Spanish English Verbal Learning Test (SEVLT-total and SEVLT-DR), and the Animal Naming (semantic fluency) and FAS (phonemic fluency). As in Xia et al (submitted), we call the first (dominant) factor "Executive Function" because it loaded strongly on processing speed and executive function tasks (e.g., Digit Symbol Substitution, Trail Making Tests, and Digit Span Test), though it will closely resemble general cognitive ability or fluid intelligence (Duncan et al., 2000), which has previously been associated with TBV and WML. The second factor loaded more strongly on scores from the two memory tests (Logical Memory and SEVLT), which is why we distinguish it as Episodic Memory (and relate to HV instead).

2.5. Dementia status

Cognitive status in the HABS-HD cohort is classified as Cognitively Unimpaired (CU), Mild Cognitive Impairment (MCI), or Dementia, using a standardized algorithmic decision tree, followed by adjudication by an interdisciplinary clinical consensus panel. An informant interview was conducted to complete the CDR scale, administered by clinicians with expertise in dementia assessment, and both CDR scores and cognitive test performance were considered in making the diagnosis (for further details, see O'Bryant et al., 2021; Petersen et al., 2025). Because the number of confirmed Dementia cases was small within several analytic subgroups, for present purposes we grouped individuals diagnosed with MCI or Dementia at Baseline into a single "Probable Dementia" (PD) group to ensure adequate statistical power (while all others were Cognitively Unimpaired, CU). For the cross-sectional (baseline) analysis, PD was based on a diagnosis at baseline only; whereas for the longitudinal analysis, PD was restricted to participants classified as CU at baseline, but who converted to PD at any of the subsequent visits. Therefore, participants who already had PD at baseline, including those with stable PD across follow-up, were excluded from the longitudinal analyses. The distribution of these groups is reported in Table S9. Although predictors of PD conversion have been examined in our previous work (Xia et al., 2026), predicting conversion was not the primary aim of the present study; here, dementia-status classification was used to support interpretation of the longitudinal cognitive and brain–cognition findings.

2.6. Statistical analysis

Analyses were performed in R (Version 4.4.2). We utilized linear

models for cross-sectional data and linear mixed-effects (LME) models for longitudinal data, with participant-level random intercepts to account for repeated measures. Overall effects were evaluated using type-II ANOVA from the *car* package, and effect sizes reported in terms of partial eta-squared (η_p^2).

2.6.1. Baseline (Cross-sectional) analyses

Our first three pre-registered hypotheses (see https://osf.io/dxrqz/files/aqgc5) concerned Brain Reserve, by testing whether bilingualism was associated with larger baseline values of TBV and HV, and smaller values of WML. All models were adjusted for ethnicity, gender, education, and age (modelled as a second-order polynomial). TIV was included as a covariate in all models to adjust for individual differences in overall head size. Continuous variables (age, education, and TIV) were z-scaled. Full model specifications, including all covariates, are reported in the corresponding tables in the Supplementary Materials.

Our next three hypotheses concerned Cognitive Reserve, by testing whether bilingualism attenuated the relationship between each brain measure and cognitive performance at baseline (making the brain-cognitive relationship less positive for TBV and HV, and less negative for WML). More specifically, the first of these hypotheses tested this directional interaction between bilingualism and TBV in predicting Executive Function, the second tested the interaction between bilingualism and HV in predicting Episodic Memory, and the third tested the interaction between bilingualism and WML in predicting Executive Function.

In all models, the normality of the residuals was examined with Q-Q plots. However, variations from normality (including kurtotic distributions) were not deemed important given the large sample size and the Central Limit theorem. Homoscedasticity was assessed via Scale–Location plots. Data points with high leverage and high residuals (based on the "*dffit*" metric in the "*influence.measures*" R function) were removed and the model re-run, to ensure robust results.

In subsequent exploratory analyses (not pre-registered), we tested further predictions of the Cognitive Reserve hypothesis (see Introduction), namely that any interactions between bilingualism and a brain measure would depend on whether a participant was likely to be suffering from a neurodegenerative disease. Specifically, cognitive performance was the outcome, and we tested the three-way interaction between bilingualism, brain measure and CU/PD group in predicting cognitive performance.

2.6.2. Longitudinal analyses

To test longitudinal changes in the brain measures, we used LMEs, in which ageing was parametrised in terms of baseline age (A0) and the time since baseline (dA). Participants had between 2 and 4 timepoints, and therefore effect of dA refers to the linear effect of time (rate of change), though the models also included the interaction between dA and A0, in order to capture nonlinear change that depended on baseline age, and also allowed this to interact with bilingualism. To test the Brain Maintenance account however, we were specifically interested in the bilingualism x dA interaction, with the prediction that bilingualism would slow the decline of TBV and HV, and slow the increase in WML.

Testing the Cognitive Reserve account is slightly more problematic because the brain and cognitive measures were not assessed at the same time points, precluding a single LME like above. We therefore estimated the change (slopes) of TBV, HV, WMH, Executive Function and Episodic Memory separately for each participant, and then tested whether the relationship between those slopes depended on Bilingualism. For the Executive Function and Episodic Memory slopes, we first adjusted the cognitive scores for practice effects, by including timepoint (wave) as a categorical factor, along with baseline age (A0), when predicting those scores across all participants using an LME. Finally, we used a linear model to test for the interaction between bilingualism and brain slope in predicting cognitive slope, while also adjusting for education, ethnicity and gender (for more rationale and code, see https://osf.io/dxrqz/overview).

In some final exploratory analyses, based on the proposal that the effects of Cognitive Reserve might differ for those who do, versus do not, develop dementia, we added the group factor of CU versus PD, to see any interactions between bilingualism and brain slope themselves depended on dementia status. Specifically, cognitive slope was the outcome, and we tested the three-way interaction between bilingualism, brain slope, and CU/PD group in predicting cognitive slope.

2.6.3. Sensitivity analyses

To assess whether the bilingualism-related effects observed in the full sample were influenced by the uneven distribution of bilingualism across ethnic groups, we conducted sensitivity analyses restricted to Hispanic participants (see Supplementary Section 3), who had the most balanced distribution of bilinguals and monolinguals. We repeated the main baseline and longitudinal models within this subgroup, using the same covariate structure as in the full-sample analyses (but without ethnicity covariate). These analyses were conducted to examine whether the main findings were robust within the ethnic group in which bilingual and monolingual participants were most directly comparable.

Also, to assess potential selective attrition in the longitudinal sample, we conducted additional sensitivity analyses (see Supplementary Section 4) comparing participants with follow-up data (i.e., Returners; $\geq$2 visits) with those who had baseline data only (i.e., Non-returners). Specifically, we fitted covariate-adjusted linear models comparing returners and non-returners on all baseline cognitive and brain measures, including Follow-up Group, Bilingualism, and their interaction. The Follow-up Group $\times$ Bilingualism interaction tested whether baseline differences between Returners and Non-Returners varied by bilingualism status. Models were adjusted for ethnicity, gender, age, education years, and TIV, consistent with the main analyses. Among participants with repeated assessments, we also conducted dropout-pattern analyses to test whether follow-up pattern moderated bilingualism-related longitudinal change and participant-level brain and cognitive slopes. We defined three Dropout groups, based on participants who attended the second assessment only, the third assessment (with or without second assessment) and the fourth assessment (with or without second and third assessments). These analyses were conducted to assess whether selective attrition may have systematically affected the main bilingualism-related findings.

2.7. Hypotheses and correction protocol

As outlined above, there were 6 pre-registered directional (one-tailed) hypotheses for each of the two analyses (cross-sectional and longitudinal). To control the family-wise error rate at 0.05 within each of these two families, we used the Holm–Bonferroni procedure of testing against ranked thresholds. Furthermore, because large samples can yield statistically significant results for negligible effects (the Jeffreys–Lindley paradox), we additionally capped the Holm-adjusted significance thresholds at N^-0.5 (Naaman, 2016). For the cross-sectional analysis (N = 3655), this yielded ascending alpha thresholds of [0.0083, 0.0100, 0.0125, 0.0165, 0.0165, 0.0165]; for the longitudinal analysis (N = 1471), the corresponding thresholds were [0.0083, 0.0100, 0.0125, 0.0167, 0.0250, 0.0261].

All raw data and R code associated with analyses are available on OSF: https://osf.io/dxrqz/overview.

3. Results

3.1. Baseline (Cross-sectional) analysis

3.1.1. Sample characteristics

The baseline dataset included 3655 participants (monolinguals: 2717; bilinguals: 938). This sample size differs slightly from the pre-registered total ($N = 3656$) due to the exclusion of one statistical outlier on HV before data harmonization. Participants' demographic

characteristics are presented in Table 1. Ethnic composition differed markedly: bilingual participants were predominantly Hispanic (82.8%), whereas monolingual participants were more likely to be White (42.8%) or Black (35.4%) ($\chi^2(2) = 1122.50$, $p < .001$). This is why Ethnicity was included an additional factor in the analyses below, i.e., to ensure any effects of bilingualism were not confounded by ethnicity. Bilingual participants had lower levels of education compared to monolinguals ($\chi^2(1) = 51.00$, $p < .001$), and were slightly younger ($\chi^2(1) = 26.10$, $p < .001$), which is why we also covaried education and a second-order polynomial effect of age. There was a trend for bilinguals to have higher (TIV), $\chi^2(1) = 3.84$, $p = .049$, so TIV was also added as a covariate when predicting brain measures. While the gender distribution did not differ significantly between groups ($\chi^2(1) = 0.93$, $p = .34$), we also covaried gender. The proportion of people with Probable Dementia was higher in monolinguals than in bilinguals ($\chi^2(1) = 5.34$, $p = .021$).

3.1.2. Effects of bilingualism on baseline brain (Brain Reserve)

For our three directional hypotheses about Brain Reserve, bilinguals showed the numerically opposite of the expected pattern, i.e. smaller rather than larger TBV and HV, and more rather than fewer WMLs (see Figure 2A). As a consequence, the main effect of bilingualism was not significant on 1) TBV, $t(3606) = -1.33$, $p = 1$, $\eta^2_p < .001$, 2) HV, $t(3596) = -1.78$, $p = 1$, $\eta^2_p < .001$, nor 3) WML, $t(3598) = 0.80$, $p = 1$, $\eta^2_p < .001$. The effects of other covariates in the model are reported in Supplementary Section 1.2.

Exploratory analyses, in which we added dementia status (Probable Dementia, PD vs. Cognitively Unimpaired, CU) to the model, did not reveal any two-way interaction between bilingualism and baseline brain measures that survived correction (TBV: $F(1, 3598) = 3.08$, $p = .080$, $\eta^2_p < .001$; HV: $F(1, 3586) = 4.71$, $p = .03$, $\eta^2_p = .001$; WML: $F(1, 3588) = 0.55$, $p = .46$, $\eta^2_p < .001$) (see Supplementary Section 1.2.4 and Figure S3A).

3.1.3. Moderation of brain–cognition relationships (Cognitive Reserve)

For our first hypothesis about Cognitive Reserve, there was a significant Bilingualism × TBV interaction on Executive Function in the predicted direction, $t(3573) = -2.30$, $p = 0.011$, $\eta^2_p = .001$, whereby the positive relationship was attenuated for bilinguals (Figure 3A, left). Analysis of the simple effects indicated that greater TBV was associated with better Executive Function in both monolinguals (β=0.36, 95% CI [0.30, 0.41]) and bilinguals (β=0.34, 95% CI [0.23, 0.45]), but less so in bilinguals.

A similar pattern was observed for the second hypothesis relating HV and Episodic Memory, with a significant Bilingualism × HV interaction, $t(3605) = -4.69$, $p < .001$, $\eta^2_p = .006$, indicating a less positive brain–cognition association in bilinguals (Figure 3A, middle). Simple effects indicated that greater HV was associated with better Episodic Memory in monolinguals, (β=0.24, 95% CI [0.20, 0.28]), but not in bilinguals (β=0.07, 95% CI [−0.01, 0.14]).

For the third Cognitive Reserve hypothesis, the interaction was in the predicted direction, i.e., an attenuation of the negative relationship between Executive Function and WMLs in Bilinguals (Figure 3A, right), but the Bilingualism × WML was not significant, $t(3582) = 1.60$, $p = .055$, $\eta^2_p < .001$.

Exploratory analyses including Dementia Status showed no three-way interactions that survived correction for TBV-EF: $F(1, 3563) = 0.54$, $p = .464$, $\eta^2_p < .001$ or HV-EM: $F(1, 3593) = 5.11$, $p = .024$, $\eta^2_p = .001$. In contrast, a significant three-way interaction merged for: WML-EF, $F(1, 3571) = 7.14$, $p = .008$, $\eta^2_p = .002$. Further analyses split by PD and CU indicated that, bilingualism significantly moderated the WML-EF association in the PD group, $F(1, 921) = 6.56$, $p = .011$, $\eta^2_p = .007$, but not in the CU group, $F(1, 2643) = 0.73$, $p = .394$, $\eta^2_p < .001$ (see Supplementary Section 1.2.4 and Figure S4A).

3.2. Longitudinal analysis

In the longitudinal sub-sample, 477 participants were classified as bilingual and 994 as monolingual. The demographics of this sub-sample are presented in Table S9 of Supplementary Material.

3.2.1. Effects of bilingualism on brain change (Brain Maintenance)

There were no significant differences in rates of brain aging between monolinguals and bilinguals. The interaction between dA and Bilingualism was not significant for TBV, $t(2202) = -1.34$, $p = 1$, $\eta^2_p < .001$, and HV, $t(2196) = 0.74$, $p = .23$, $\eta^2_p < .001$, indicating comparable declines across groups. WML accumulation also did not differ significantly between groups after correction, $t(2197) = -2.11$, $p = .018$, $\eta^2_p = .002$ (see Figure 2B).

In exploratory analyses including Dementia Status (i.e., Stable CU vs. PD Converters), there was no significant three-way interactions between Dementia Status, Bilingualism and dA on any brain measure (TBV: $\chi^2(1) = 0.01$, $p = .917$, $\eta^2_p < .001$; HV: $\chi^2(1) = 0.19$, $p = .67$, $\eta^2_p < .001$; WML: $\chi^2(1) = 0.65$, $p = .419$, $\eta^2_p < .001$). However, the four-way interaction between Dementia Status, Bilingualism, A0 and dA was significant in HV, $\chi^2(1) = 7.10$, $p = .008$, $\eta^2_p = .004$. To unpack this four-way interaction, we tested the Bilingualism-by-dA interaction separately for four groups formed by younger versus older (relative to median) and CU versus PD (see Figure S5). The only significant such interaction occurred in the older, CU group, in which bilinguals showed a shallower decline than monolinguals, $t(698) = -2.28$, $p = .02$ (bilingual: $b = -0.05$, $SE = 0.02$; 95% CI [–0.08, –0.02]; monolingual: $b = -0.09$, $SE = 0.01$, 95% CI [–0.11, –0.07]) (see Supplementary Section 2.2.4).

To further align the analyses with the Brain Maintenance framework, we also examined whether longitudinal brain-change slopes predicted cognitive-change slopes. These analyses were reported in Supplementary Materials Section 2.3, Tables S15–S17. Brain-change slopes significantly predicted cognitive-change slopes: TBV change was associated with executive-function change, $F(1, 1429) = 33.99$, $p < .001$, $\eta^2_p = .022$; HV change was associated with episodic-memory change, $F(1, 1432) = 9.80$, $p = .002$, $\eta^2_p = .007$; and WML change was associated with executive-function change, $F(1, 1432) = 37.51$, $p < .001$, $\eta^2_p = .030$.

3.2.2. Moderation of change-change relationships (Cognitive Reserve)

To test cognitive reserve over time, we examined whether bilingualism moderated the association between longitudinal brain change and longitudinal cognitive change. Specifically, we tested brain slope × bilingualism interaction terms predicting cognitive slopes. While Executive Function slopes were positively associated with TBV slopes, as

Table 1
Demographic Characteristics of Monolingual and Bilingual Participants (Cross-Sectional Sample).

Variable	Monolingual	Bilingual	*p*
N	2717	938	
Age, mean (SD)	65.67 (8.70)	63.91 (8.44)	< .001
Gender, n (%)			.335
Male	1013 (37.3)	367 (39.1)	
Female	1704 (62.7)	571 (60.9)	
Education, years (SD)	13.59 (4.29)	12.74 (4.03)	< .001
Ethnicity, n (%)			< .001
Hispanic	593 (21.8)	777 (82.8)	
White	1162 (42.8)	131 (14.0)	
Black	962 (35.4)	30 (3.2)	
TIV, litres (SD)	1.424 (0.168)	1.410 (0.166)	.050
Dementia status, n (%)			.021
CU	1949 (71.9)	711 (75.9)	
PD	761 (28.1)	226 (24.1)	

Note. Values are reported as M (SD) for continuous variables and n (%) for categorical variables. Group differences in age and years of education were assessed using Kruskal–Wallis tests due to non-normal distributions. Gender and ethnicity differences were assessed using chi-square tests.

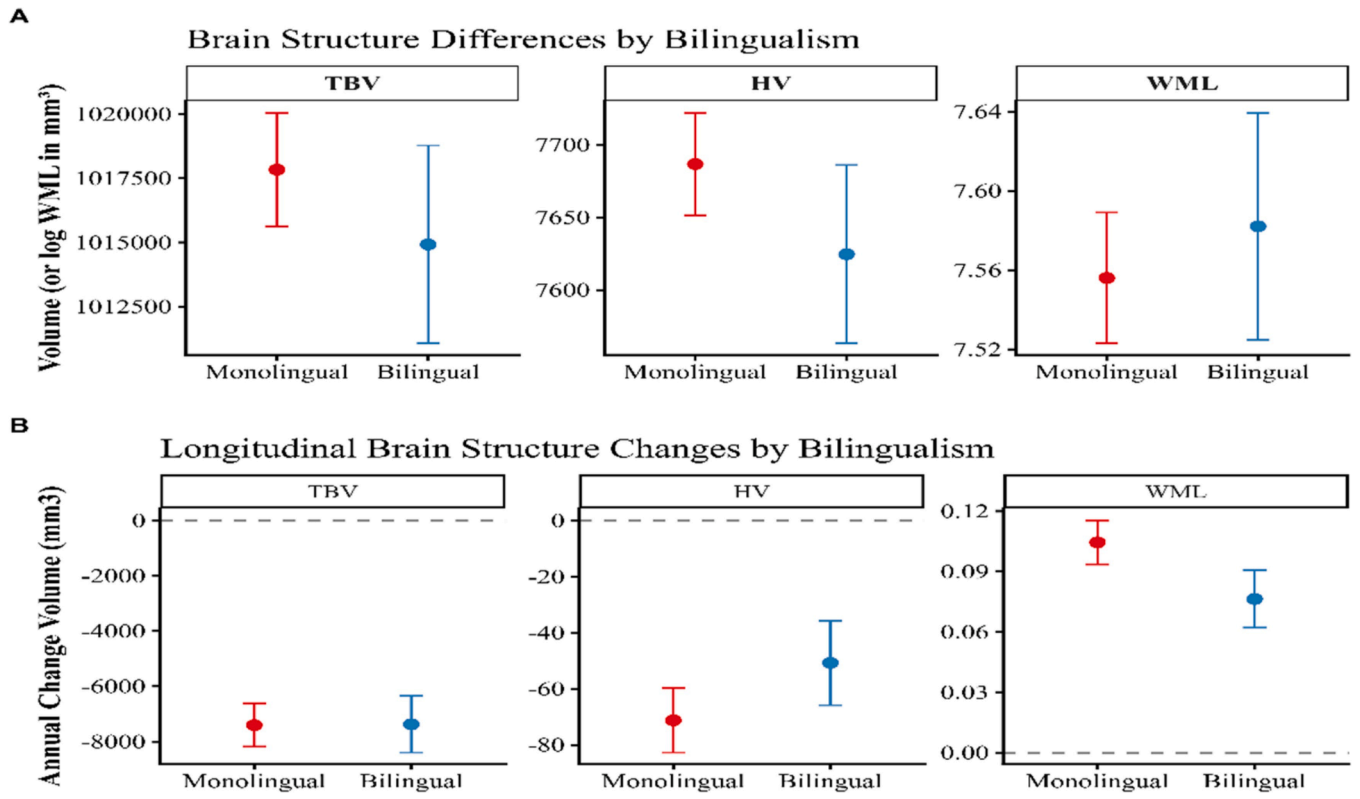

Fig. 2. Testing Brain Reserve and Brain Maintenance. (A) Baseline volumes for Total Brain Volume (TBV), Hippocampal Volume (HV) and White Matter Lesions (WML) for Monolinguals (red) and Bilinguals (blue). Influential outliers were excluded from analyses to ensure robustness ($N_{excluded}$: TBV=40, HV=50, WML=48). (B) Annualized rates of change for the same neuroanatomical markers. Points represent estimated marginal means adjusted for age, gender, ethnicity, education and TIV; error bars denote 95% confidence intervals.

expected (Figure 3B; see Supplementary Material for statistics), but the TBV slope × bilingualism interaction was not significant, $t(1, 1429) = 0.35$, $p = 1$, $\eta^2_p < .001$. Similarly, the HV slope × bilingualism interaction was not significant for Episodic Memory slopes, $t(1, 1432) = 0.20$, $p = 1$, $\eta^2_p < .001$, and the WML slope × bilingualism interaction was not significant for Executive Function slopes, $t(1, 1432) = 0.27$, $p = 0.39$, $\eta^2_p < .001$.

Exploratory analysis that added Dementia Status as factor to the above slope-slope models revealed a significant three-way interaction between Dementia Status, bilingualism, and TBV slope in predicting Executive Function slope, $F(1, 1100) = 7.98$, $p = .005$, $\eta^2_p = .007$. Follow-up analyses suggested a PD-specific bilingualism × TBV slope interaction, $F(1, 123) = 4.67$, $p = .033$, $\eta^2_p = .04$, but this did not survive Holm-Bonferroni correction; the CU interaction was not significant, $F(1, 972) = 2.29$, $p = .130$, $\eta^2_p = .002$. In contrast, the three-way interactions were not significant for HV–EM, $F(1, 1102) = 0.04$, $p = .835$, $\eta^2_p < .001$, or WML–EF, $F(1, 1104) = 0.12$, $p = .726$, $\eta^2_p < .001$ (see Supplementary Section 1.3.4 and Figure S4B).

3.3. Additional sensitivity analyses

3.3.1. Hispanics only analyses

In case the effect of bilingualism depended on ethnicity, we also conducted sensitivity analyses in Hispanics only, given that this group had the most equal distribution of bilinguals vs monolinguals. These analyses are reported in Supplementary Section 3. Overall, the Hispanic-only results showed a pattern broadly consistent with the full-sample analyses. Specifically, bilingualism was not significantly associated with baseline TBV, HV, or WML, nor did it moderate longitudinal change in these brain measures. The moderation effects of bilingualism for the TBV-EF ($p = .058$) and HV-EM ($p = .065$) were marginal, which could be due to smaller sample size. The longitudinal pattern was also consistent with the full-sample analyses, with no evidence that bilingualism moderated brain changes over time. In exploratory analyses of brain–cognition slopes as a function of dementia status, the Brain Slope × Bilingualism × Group interaction was significant for EF–TBV slopes, $F(1, 430) = 12.50$, $p < .001$, $\eta^2_p = .03$, and EF–WML slopes, $F(1, 427) = 5.76$, $p = .017$, $\eta^2_p = .01$, suggesting that bilingualism-related attenuation of brain–cognition coupling was most apparent among participants with probable dementia (see Figure S6).

3.3.2. Sensitivity analyses on selective attrition

Additional analyses addressing potential selective attrition are reported in the Supplementary Section 4. Briefly, participants with follow-up data differed from baseline-only participants in several baseline characteristics, including bilingualism status and cognitive performance (see Table S27). The Follow-up Group × Bilingualism interaction was not significant for any cognition measure or brain measure (see Table S28-29). Additional dropout-pattern analyses among participants with repeated assessments showed no robust evidence that follow-up pattern moderated bilingualism-related longitudinal change or participant-level brain and cognitive slopes (see Table S30-32). Overall, these analyses suggest that selective attrition was present but did not substantially bias the main bilingualism-related longitudinal findings.

4. Discussion

The present pre-registered analyses investigated the neural mechanisms underlying the cognitive advantages in bilingual relative to monolingual older adults, by distinguishing Brain Reserve, Brain Maintenance and Cognitive Reserve. When using the whole HABS-HD sample, we found no support for our operationalisations of the Brain Reserve or Brain Maintenance accounts: bilinguals did not show higher whole-brain nor hippocampal gray-matter volumes, nor less white-

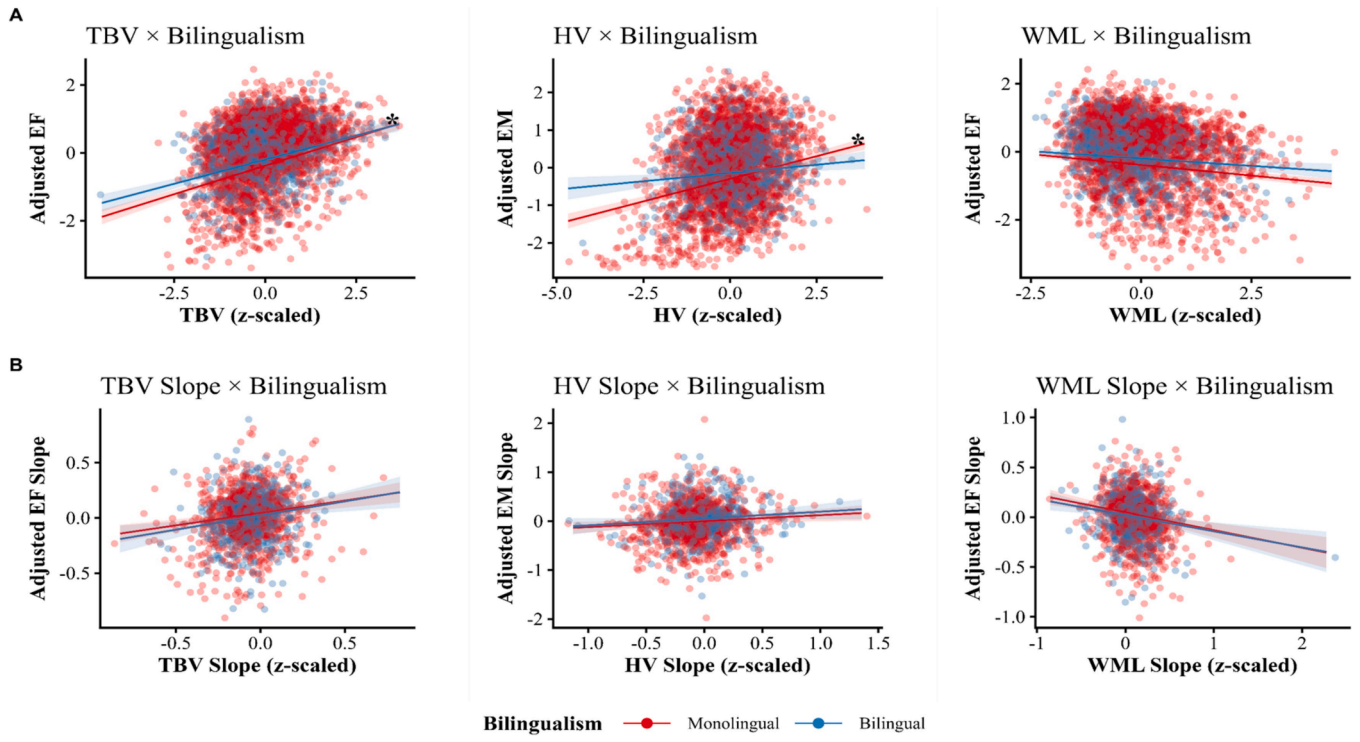

Fig. 3. Testing Cognitive Reserve. (A) Cross-sectional associations between baseline neural markers (TBV, HV, WML) and baseline cognitive domains (Executive Function [EF], Episodic Memory [EM]) for Monolinguals (red) and Bilinguals (blue) Influential outliers were excluded from analyses to ensure robustness ($N_{excluded}$: TBV-EF=67, HV-EM=35, WML-EF=58). (B) Longitudinal associations linking the rate of neural change (slopes) to the rate of cognitive decline (slopes) Influential outliers were excluded from analyses to ensure robustness ($N_{excluded}$: TBV-EF slope=25, HV-EM slope=23, WML-EF slope=21). Shaded regions indicate 95% confidence intervals. Individual points represent partial residuals adjusted for age, gender, ethnicity, education and TIV. The significant difference in slopes (interaction) suggests bilingualism reduces the dependency of cognitive function on gray-matter volume.

matter lesion volume, at baseline, nor reduced rates of subsequent changes in these brain measures. However, we did find support for the Cognitive Reserve account, at least in the baseline cross-sectional analyses, whereby the relationships between executive function and whole-brain volume, and between episodic memory and hippocampal volume, were less positive in bilinguals than monolinguals, suggesting that bilingualism compensated for individual variation in these structural brain measures (Barulli and Stern, 2013), presumably through some other neural mechanism not measured here (Henson, 2026).

We did not find any evidence that bilingualism moderated the longitudinal relationships between subsequent cognitive decline and subsequent changes in our brain measures, which would further support Cognitive Reserve. This could mean that the cross-sectional moderations that we did observe at baseline reflect other individual differences that happen to correlate with bilingualism; or else, it could reflect reduced statistical power for longitudinal analyses (see later for further discussion). However, yet another possibility is that the effects of bilingualism, as a form of Cognitive Reserve, differ according to dementia status. This is because previous studies have argued that Cognitive Reserve might protect cognition up to some limit of brain damage (due to ageing or neurodegenerative disease), but eventually become unable to compensate beyond that limit, such that individuals beyond that limit show more dramatic declines in cognition, or possibly even no longer show a cognitive advantage of bilingualism (Berkes et al., 2020; Perani et al., 2017). In exploratory analyses, we therefore split the HABS-HD sample into those with probable dementia (using clinical data) versus those who were cognitive unimpaired. Interestingly, we found some suggestions that the effects of bilingualism on hippocampal volume, and its relationship to episodic memory, did depend on dementia status, as we unpack below.

4.1. Brain reserve

We found no evidence that bilingualism (earlier in life) affects the amount of Brain Reserve when entering old age. Our lack of such baseline differences in whole-brain, hippocampal and white-matter lesions between bilingual and monolingual groups contrasts with previous claims that bilingualism is associated increased gray-matter volume in language- and cognition-related brain regions, including the hippocampus (Abutalebi et al., 2015; Abutalebi et al., 2015; Heim et al., 2019; Olsen et al., 2015; Voits et al., 2022). We do not think the lack of differences reflects insufficient power, since our sample size is much bigger than most previous studies. Rather, the discrepancy with previous studies could reflect a focus on different brain regions, controlling for different potential confounds, or even heterogeneity in sample characteristics across studies, such as age / length of bilingual experience (García-Pentón et al., 2016). For example, while our raw (unadjusted) values did indicate a "bilingual advantage" (i.e., larger hippocampal volumes and lower white matter lesion loads), adjusting for our (pre-registered) confounding covariates reversed this pattern, revealing numerically, but not significantly, lower hippocampal volumes and higher lesion loads, in the bilingual group. Thus, it is important to note that, while we failed to find support for the Brain Reserve account of bilingualism, once adjusting for confounds, our findings should not be taken as evidence against it.

One framework consistent with the present null findings is the Dynamic Restructuring Model (Pliatsikas, 2020), which proposes a non-linear trajectory, in which early bilingual experience is associated with volumetric expansion, followed by neural reorganization and efficiency gains that may return macroscopic volume to baseline levels. Importantly, this model does not predict stable volumetric differences at all stages of bilingual experience. Evidence from clinical populations further supports a cautious interpretation of structural measures:

bilingual individuals with Alzheimer's disease have been shown to exhibit greater atrophy than monolinguals at comparable cognitive impairment, a pattern often interpreted as consistent with Cognitive Reserve (Perani et al., 2017), though any such effects did not reach significance in our exploratory analyses.

4.2. Brain maintenance

Our a priori, pre-registered tests did not provide any evidence that bilingualism affects the subsequent rate of change of our brain measures either, i.e., no evidence that it improves Brain Maintenance. To our knowledge, longitudinal evidence on within-individual brain changes associated with bilingualism in late life remains limited and domain-specific, with existing longitudinal evidence restricted to small clinical samples with short follow-up (Costumero et al., 2020), region-specific gray-matter trajectories in healthy aging (Peitz et al., 2023), or isolated neurovascular markers (Solé-Padullés et al., 2025). In our exploratory analyses, when we split individuals according to whether or not they progressed to probable dementia at some point during their assessment, we did find a suggestion that bilingualism was associated with a reduced rate of decline of hippocampal volume, but only in cognitively unimpaired individuals who were older than the median age. However, this effect was small, exploratory, and subgroup-dependent. It should therefore be interpreted as hypothesis-generating rather than confirmatory. This finding clearly requires replication, but if it does replicate, it would be consistent with bilingualism helping to maintain hippocampal volume in late life, provided dementia-related neurodegeneration has not yet taken hold. Note also that, while this pattern is compatible with a Brain Maintenance hypothesis, it could also reflect ongoing experience-dependent neuroplasticity, such that continued bilingual language use actively remodels hippocampal structure and partially offsets normative aging-related loss rather than simply preserving existing tissue (Pliatsikas et al., 2020).

4.3. Cognitive reserve

What we did find clear evidence for, was that bilingualism moderates the baseline (inter-individual) relationship between gray-matter volume and cognition, at least between whole-brain volume and executive function, and between hippocampal volume and episodic memory. Such a moderation, whereby a factor reduces the positive association between brain structure and cognition, has traditionally been taken to indicate Cognitive Reserve. This attenuation of the usual structural-cognitive relationship suggests more efficient or flexible brain–cognition relationships in bilinguals. Although functional imaging data were not analysed in the current study, this reduced association is consistent with prior work proposing that lifelong bilingual language use involves sustained engagement of cognitive control, monitoring and selection processes that recruit distributed fronto-parietal and subcortical networks (Abutalebi and Green, 2016; Pliatsikas et al., 2020). Over time, such engagement may foster more flexible coordination among control, memory and language systems, allowing cognitive performance to be supported by alternative or supplementary pathways when primary structures are compromised by age-related atrophy (Grundy et al., 2017).

In contrast to the cross-sectional findings, bilingualism did not reliably moderate associations between longitudinal changes in brain structure and longitudinal changes in cognitive performance in the full sample. This suggests that bilingual advantages in late life may be more evident in baseline differences in brain–cognition coupling (intercept effects), rather than as altered sensitivity to ongoing brain change (slope effects), consistent with a previous study (Elliott et al., 2025), where bilingualism reduced the relationship between brain and cognition at baseline but not longitudinally. This pattern may seem to differ from our previous finding that bilingualism was associated with slower episodic-memory decline in the same cohort (Xia et al., 2026). However, the studies addressed different questions: Xia et al. tested whether bilingualism predicted cognitive decline, whereas the present study tested whether bilingualism altered brain–cognition coupling over time. Thus, the current findings do not rule out bilingualism-related cognitive resilience, but suggest that the prior episodic-memory effect was not clearly explained by reduced sensitivity to the structural brain changes examined here.

Alternative explanations must also be considered. One possibility is that the cross-sectional effects of bilingualism are an artefact of some other individual difference that correlates with bilingualism. We controlled for several such variables, such as baseline age, ethnicity, gender and education, but it is always possible that the relevant variable was some other individual property (which may not even be recorded in the HABS-HD cohort). Indeed, the use of different covariates may also contribute to divergent bilingualism findings across the literature (Del Maschio et al., 2021). Conversely, the lack of longitudinal effects could reflect reduced statistical power, given the limited follow-up duration (i.e., 2–6 years), and/or measurement noise inherent to repeated structural imaging, and/or individual differences in practice effects across repeated cognitive assessment (independent of our control for average practice effects). Other studies have reported similar null results of longitudinal effects, despite cross-sectional effects (Yeung et al., 2014; Zahodne et al., 2014). Thus again, the absence of bilingualism effects on these slopes should not be taken as definitive evidence that bilingualism does not influence longitudinal brain–cognition dynamics.

Finally, exploratory analyses suggested that, in individuals diagnosed with PD, bilingualism was associated with a weaker baseline relationship between white matter lesion volume and executive function performance. Longitudinally, the Hispanic-only sensitivity analyses showed a similar pattern: bilingualism-related differences in the associating between brain change and cognitive change were most evident in participants with PD, particularly for total brain volume and white matter lesion burden in relation to executive function. This is contrary to claims that Cognitive Reserve slows decline up to some level of neurodegeneration, before leading to accelerated decline when it can no longer compensate for advanced neurodegeneration, because that would predict, if anything, the opposite pattern of a stronger relationship between white matter lesion volume and executive function performance in PD (once greater neurodegeneration), and a weaker one in the CU group (with less neurodegeneration). Conversely, it is possible that the effect of bilingualism as a form of Cognitive Reserve only emerges once neurodegeneration is established, allowing the brain to maintain cognitive function despite significant structural damage (Costumero et al., 2020; Elliott et al., 2025; Perani et al., 2017; Schweizer et al., 2012). The weaker brain–cognition coupling observed among bilinguals with PD may reflect a reduced dependence of executive function on measured structural brain integrity, rather than direct preservation of brain structure. For example, according to the Bilingual Anterior-to-Posterior and Subcortical Shift (BAPSS) framework, bilingual language control increasingly relies on subcortical and posterior circuits to maintain processing efficiency (Grundy et al., 2017). However, because these analyses were exploratory and subgroup-specific, this interpretation should be considered tentative and requires replication.

4.4. Study limitations

Several limitations of the current study warrant consideration. The observational design precludes causal inference regarding reserve accumulation. Although the models adjusted for age, ethnicity, gender and education, residual confounding by socioeconomic and contextual factors remains possible. Education was included as the main SES-related covariate, but it may not fully capture income, literacy, education quality, occupational complexity, healthcare access, or neighbourhood disadvantage. Also, we were also unable to account for

immigration history or the potential healthy immigrant effect (Markides & Rote, 2019), which may be particularly relevant in Hispanic populations. The dataset did not include information on whether participants were US-born or immigrants, country of birth, or age at immigration. This limits our ability to separate bilingualism-related effects from broader immigration-related, sociocultural, and life-course factors. Future studies with detailed immigration and contextual measures are needed. A further limitation is the limited information available on bilingualism characteristics. Bilingualism was operationalised categorically, and detailed measures of age of acquisition, proficiency, language use, dominance, literacy, and interactional context were not consistently available.

The available longitudinal window may have limited sensitivity to detect reserve effects and the absence of functional or connectivity measures constrains mechanistic interpretation. Moreover, effects restricted to the cognitively unimpaired group may partially reflect selective attrition or survivor biases (e.g., compared to others who dropped out of the HABS-HD study owing to health problems). As reported in the Supplementary Materials, participants with follow-up data differed from baseline-only participants in several baseline characteristics, although additional sensitivity analyses provided little evidence that selective attrition substantially biased the main bilingualism-related findings. Because the available data did not distinguish mortality from other reasons for missing follow-up, selective attrition remains a limitation. Future studies incorporating longer follow-up periods and multimodal imaging will be essential for clarifying how bilingual experience shapes reserve expression across disease stages.

Taken together, our results suggest that bilingualism functions as a type of Cognitive Reserve, more so than affecting Brain Reserve or Brain Maintenance, particularly in cross-sectional brain–cognition relationships. However, we found no evidence for Cognitive Reserve over time: bilingualism did not moderate the association between longitudinal brain change and cognitive decline. There was also suggestive evidence that the effects of bilingualism depend on the clinical status of dementia (and assumed degree of neurodegenerative disease), at least for hippocampal volume and episodic memory. The latter clearly warrants further replication and extension, particularly with longitudinal designs to measure within-individual changes that are less confounded by other individual differences. Nonetheless, by adopting a stage-sensitive reserve framework, the present study may help reconcile mixed findings in the bilingualism literature, and underscores the complexity of experiential influences on brain–cognition relationships in later life.

Author declarations

All authors contributed substantially to this work, had access to the data, participated in the interpretation of findings, approved the final version of the manuscript, and agree to its submission to

CRediT authorship contribution statement

Didac Vidal-Pineiro: Writing – review & editing, Methodology, Data curation, Conceptualization. **Lihua Xia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Meeker Karin:** Writing – review & editing, Resources, Data curation, Conceptualization. **Richard Henson:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Ethics approval and consent

The Health and Aging Brain Study–Health Disparities (HABS-HD) protocol was approved by the Institutional Review Board of the University of North Texas Health Science Center. Written informed consent was obtained from all participants or their legally authorized representatives prior to participation.

The present secondary analyses were approved by the Institutional Review Board of the University of Texas at Austin (STUDY00003075).

Consent statement

The HABS-HD study protocol is conducted under the University of North Texas Health Science Center, Institutional Review Board approval. Each HABS-HD partner (and/or legal guardian) provides a signed written informed consent to participate in the study.

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Declaration of Competing Interest

The authors declare no competing interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neurobiolaging.2026.09.008.

Data availability

The HABS-HD data underlying this study are available to qualified investigators through the University of North Texas Health Science Center Institute for Translational Research, subject to data use agreements.

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