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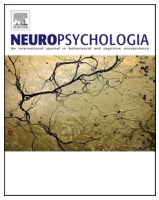

Bilingual experience affects white matter integrity across the lifespan

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ABSTRACT

Bilingualism has been associated with increases in compensatory mechanisms to age-related neurocognitive decline thus delaying dementia symptom onset and leading to a more favorable trajectory of neurocognitive aging. However, most research to date has examined bilingualism-induced effects on neurocognition *within* older age ranges or young adults – with middle-aged individuals typically not being a population of interest. Furthermore, bilingualism is often treated as a dichotomous variable, despite it being a heterogeneous experience on an individual level. In the present study, we employed diffusion tensor imaging (DTI) to examine whether bilingualism, and the degree of engagement in bilingual experience, modulates the nature or rate of white matter decline associated with aging. DTI data and language history data were collected from a cohort of monolingual and bilingual individuals spanning a wide age range. Two separate analyses were run. First, generalized additive models were run on matched monolingual and bilingual samples, examining effects of age on the trajectory of white matter integrity and how bilingualism modulates this effect. This analysis revealed a significant effect of age within the monolingual group for fractional anisotropy values in the right superior longitudinal fasciculus. However, the age effect within the bilingual group was not significant, indicating a faster decline in white matter integrity within the monolingual cohort. Second, general linear models were run on the entire participant sample, examining an interaction between age and degree of bilingual engagement on white matter integrity. Results from this analysis indicate that increased engagement in bilingual language use across the lifespan correlates with a slower decline in white matter integrity with age. Together these results indicate bilingualism, and specifically degree of bilingual engagement, impacts the trajectory of age-related decline in white matter integrity across the lifespan.

1. Introduction

Bilingualism has been proposed as a lifestyle factor that ameliorates the neuroanatomical and cognitive decline associated with healthy aging (Bialystok, 2021; Grant et al., 2015). Previous studies have shown that healthy adult bilingual individuals exhibit evidence for accrual of a brain reserve (Gold, 2015; Zhang et al., 2020). This manifests as a combination of adaptations in gray matter volume, white matter (WM) integrity, and greater structural and functional integrity of brains in bilinguals when compared to matched monolinguals. This neural restructuring is thought to lead to a more favorable trajectory of neurocognitive aging in the later years of life. Through reserve mechanisms, bilingualism may also delay the onset of dementia symptoms (Anderson et al., 2020; Brini et al., 2020). However, this evidence is commonly reported as a cross-sectional, between groups (monolingual vs. bilingual) comparison. Less is known about how bilingual experience interacts with age to impact the nature and *trajectory* of this decline. Furthermore, although bilingual experience is quite heterogeneous (see, e.g., Bak, 2016; Luk and Bialystok, 2013), little evidence currently exists regarding how varying degrees of bilingual engagement might affect this trajectory. The aims of the present study were, thus, 1) to examine how bilingualism affects the trajectory of neurostructural decline in aging, and 2) assess how degree of bilingual experience might ameliorate the rate of neural decline.

White matter is a crucial element in the neural architecture that ensures communication between different brain regions. Normal aging produces trends of diminishing WM integrity (Bartzokis et al., 2012; Bennett et al., 2010; Cox et al., 2016; Imperati et al., 2011). White matter decline has been mapped throughout healthy aging and can be detected earlier than aging-related gray matter atrophy (Giorgio et al., 2010). After reaching a peak between 20 and 42 years of age, declines in both WM volume and integrity occur across multiple tracts (Lebel et al., 2012). This trajectory is not always linear. Regional and global WM integrity has been found to remain relatively constant through

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adulthood and then to more sharply decline later in life, beginning around the age of 60 (Westlye et al., 2010). But, even if some decline is inevitable with age, maintenance of WM integrity is of paramount importance in aging as reductions in WM volume and integrity have been linked to cognitive outcomes not only in healthy aging (Kerchner et al., 2012), but also in neurodegenerative diseases such as Alzheimer's disease (Gold et al., 2012), Parkinson's disease (Auning et al., 2014; Hattori et al., 2012), Huntington's disease (Ciarmiello et al., 2006; Novak et al., 2014) and Multiple Sclerosis (Riccitelli et al., 2012). Moreover, WM integrity, even in midlife, predicts neurocognitive health and outcomes as time passes (Irwin et al., 2018).

Crucially, the decline of WM integrity can be modulated by various lifestyle factors. A number of these including physical exercise (Hötting and Röder, 2013; Young et al., 2015), musicianship (Andrews et al., 2021) and educational attainment (Mungas et al., 2018) have been shown to offer some degree of protection against the symptoms of neurocognitive aging. In recent years, a growing body of work indicates bilingualism, as a lifestyle factor, might provide a similar type of protection (see for review Gallo et al., 2020; Zhang et al., 2020). The continued management of two competing linguistic systems is thought to result in specific neurophysiological adaptations in regions involved in language and domain-general cognitive control which, in turn, make the brain more effective and efficient at handling these control demands (Li et al., 2014; Pliatsikas, 2020; Pliatsikas et al., 2020). These bilingualism-induced neuroanatomical adaptations are thought to provide a basis for brain reserve seen in typical aging (Abutalebi and Green, 2016; Grant et al., 2014; Grundy et al., 2017). We herein refer to brain reserve as the structural reinforcement or "scaffolding" of gray- and WM integrity against the natural decay associated with aging (Stern et al., 2020).

Previous research has shown bilingualism contributes to the building-up of brain reserves in older age (Calabria et al., 2018). Studies employing diffusion tensor imaging (DTI) have found that older bilinguals maintain higher integrity in several WM tracts supporting language processing and control, specifically the corpus callosum (CC), superior longitudinal fasciculi (SLF) bilaterally, and right inferior fronto-occipital fasciculus (IFOF) (Anderson et al., 2018a; Luk et al., 2011). For example, Anderson et al. (2018) found bilinguals to exhibit higher integrity in temporal regions of the SLF; the higher WM integrity observed for bilinguals was interpreted as increased neural reserve to counteract symptoms of decline. Bilingualism has also been found to contribute to changes in functional connectivity in older age, which seem to relate to adaptations in WM microstructure (Luk et al., 2011). However, this pattern of results is not uniform across studies. Several show bilingual older adults to have *lower* preservation of WM integrity in older age when compared to monolingual controls. For example, a study by Gold et al. (2013) found that while older bilinguals performed similarly to monolinguals on several executive function (EF) tasks, they exhibited lower WM integrity in a number of brain regions, including the inferior longitudinal fasciculus (ILF) and the IFOF, the fornix, and multiple portions of the CC. More recent work by Anderson et al. (2021) shows similar effects- bilinguals and monolinguals performed similarly on various cognitive measures with bilinguals exhibiting a generally greater degree of brain structure decline.

The current evidence for bilingual effects on WM decline in aging is mixed. However, the majority of evidence for this comes from cross-sectional, group-level comparisons. More recent proposals (e.g., Bialystok, 2021; Perani and Abutalebi, 2015) suggest a *shifting* trajectory of brain structure decline through aging as the brain shifts from a mechanism of resilience to one of compensation. That is, in earlier stages of aging, bilingual experience may contribute to resilience against structural degradation (Gallo et al., 2020; Perani and Abutalebi, 2015). However, in later stages of aging, when these physical reserves are exhausted, a compensatory mechanism is engaged to maintain cognitive performance with diminishing neural resources (Bialystok, 2021). Such a trajectory is difficult to capture with group-level comparisons. To our knowledge, very few studies to date have examined what effect bilingual experience has on the actual *trajectory* of neural decline through aging (but see Anderson et al., 2021).

Another potential source of variability in bilingualism-related neurocognitive outcomes in aging is the bilingualism itself. Bilingual experience is not static or uniform across individuals (Bak, 2016; Leivada et al., 2021; Luk and Bialystok, 2013) and this has implications for neurocognitive outcomes. In younger populations, a growing body of research shows that individual bilingual experiences correlate to distinct neurocognitive outcomes (Beatty-Martínez et al., 2020; DeLuca et al., 2019; Fedeli et al., 2021; Gullifer et al., 2018; Navarro-Torres et al., 2021; Sulpizio et al., 2020). Two key trends can be seen from this literature. First, engagement with different bilingual experience-based factors (e.g., duration of use, degree and nature of switching, etc.) correlate with distinct and specific neurocognitive adaptations. Second, these adaptations are dynamic in their instantiation and are calibrated to the nature and degree of experience (see for review DeLuca et al., 2020). As the nature and degree of neural plasticity is linked to patterns of language experience, it follows that this would have implications for the degree of neurocognitive decline associated with aging. However, very little research to date has examined this relationship. An ongoing question thus remains- how do different degrees of engagement with bilingual experience correlate to plasticity, juxtaposed against neural decline associated with aging?

1.1. The present study

Given the above discussion, the specific aims of the present study are twofold. First, we aim to assess how bilingualism as an experience modulates the trajectory of WM decline in healthy aging. Second, we aim to examine the extent to which the degree of engagement in bilingual experience might ameliorate the trajectory for WM integrity across the adult lifespan. We specifically examine two commonly used measures of WM integrity: fractional anisotropy (FA), a measure of the orientation of water diffusion in the myelinated axons, and mean diffusivity (MD) a measure of overall rate of water diffusion in brain tissue, to check patterns of WM microstructure and a more broad measure of degree of myelination (Bennett et al., 2010). Reductions of WM integrity are expressed as increases in MD values and decreases in FA values. Given study aims, our predictions were the following: First, we predicted that bilingual experience would delay the onset of any trend of increased demyelination (Anderson et al., 2018a; Bialystok, 2021; Luk et al., 2011). Second, given the correlations to increased plasticity in younger adults we predicted that increased engagement with bilingual experience would result in a further degree of delay in WM decline.

2. Methods

2.1. Participants and procedure

In total, 78 participants (56 female, *m*age = 51.6, range: 30–83) were included in the subject cohort. Inclusion criteria for the study were being right-handed, no history of speech and language disorders, and no contraindications to MRI scanning. This cohort consisted of a bilingual group of a wide age range and monolingual group who were middle-to-older-aged (see Table 1 for demographic information on the participant sample). The bilingual participants spoke a range of additional languages, but all spoke English. The monolingual participants were native speakers of English with minimal to no exposure to any additional languages. All participants were resident in the UK at time of testing. In addition to the scan, participants completed the Language and Social Background Questionnaire (LSBQ; Anderson et al., 2018b), which documents participants' language exposure and use in a variety of settings. The LSBQ contains a factor score calculator with a variety of outputs, including a bilingual composite factor score (BCS) relating to overall degree of bilingual engagement. For the BCS, a higher score indicates a

Table 1
Characteristics of the participant sample. The matched dataset was used for the between-groups analyses. *ACE-III scores only available for a subset of participants.

	Participants (N = 78)	Matched Monolinguals (N = 22)	Matched Bilinguals (N = 22)
Mean age (SD)	51.6 (14.2)	63.7 (9.81)	57.9 (6.34)
Sex	56 F; 22 M	12 F; 10 M	15 F; 7 M
Education (SD)	4.10 (1.15)	3.36 (1.14)	3.82 (1.10)
LSBQ Bilingualism Composite Score (SD)	9.59 (10.9)	−5.82 (1.65)	17.0 (3.51)
ACE-III total score (SD)	N/A*	94.8 (4.06)	94.6 (3.76)
Contrast-to-noise ratio (SD)	1.01 (0.154)	1.05 (0.147)	1.10 (0.150)
Signal-to-noise ratio (SD)	27.2 (3.28)	27.4 (2.80)	28.5 (2.57)
Absolute motion in the scanner (mm) (SD)	0.768 (0.408)	0.720 (0.334)	0.636 (0.178)

greater degree of bilingual engagement, whereas a lower score indicates a lower degree of engagement. In addition to the quantification of bilingualism, we also calculated a score related to education level for use in analyses. A question pertaining to education level was re-coded to reflect a Likert scale indicating the highest level of education achieved. Scores were as follows: 1: no secondary education, 2: school (e.g., high school diploma, A-levels, etc.), 3: some undergraduate education, 4: undergraduate degree or diploma, 5: graduate or professional-level degree. A subset of participants towards the older end in the age spectrum (aged 48 and above, apart from one participant) also completed Addenbrookes Cognitive Examination (ACE-III) (Hsieh et al., 2013). ACE-III is a widely used cognitive screening tool and covers five cognitive domains – attention, memory, fluency, language, and visuo-spatial processing. A score of at least 82 out of 100 indicates healthy cognitive function.

2.2. Imaging data acquisition

MRI scanning was performed on a Siemens 3T Prisma scanner with a 32-channel head coil and Syngo software. Participants underwent a diffusion tensor imaging scan (voxel size 2.0 mm isometric, TR = 1800 ms, TE = 70 ms, 64 directions, FOV = 260 mm). For purposes of pre-processing, a reverse phase-encoded b0 image and volumes with the otherwise same parameters were obtained directly after the DTI scan.

2.3. Data preprocessing and analysis

DTI data were preprocessed with pipelines within FSL (Jenkinson et al., 2012). The data were first preprocessed using the *topup* (Andersson et al., 2003) and *eddy* (Andersson and Sotiropoulos, 2016) pipelines to account for susceptibility distortions, eddy current distortions, and any signal outliers within volumes. As diffusion MRI data quality can be affected by subject-related artefacts, the *eddyqc* automated quality control pipeline was run to assess the data at a subject level (Bastiani et al., 2019). Through this method, measures of contrast-to-noise ratio (CNR), signal-to-noise ratio (SNR), and absolute motion in the scanner were obtained (see Table 1 for a summary of these metrics). Following preprocessing, a tensor model was fit using the *dtifit* pipeline within the FDT package (Behrens et al., 2007). The standard pipeline within the tract-based spatial statistics (TBSS) package was carried out. First, all subjects were non-linearly registered to a 1x1x1mm MNI-space template. From this, a mean FA image was created and then skeletonized. Finally, all subjects FA and MD values were projected on the skeletonized images. Following these steps, FA and MD values were extracted for each participant. This was done first using the whole FA skeleton to extract whole-brain FA and MD values, as a measure overall brain health (see e.g., Berkes et al., 2021), and for several ROI tracts which have been previously implicated in both bilingualism-induced plasticity and neural decline associated with aging, including the CC, bilateral IFOF, and SLF (Luk et al., 2011; Singh et al., 2018). For the ROIs, parcellations taken from the Juelich Histological Atlas were used as masks to extract FA and MD values (Fig. 2, bottom panel).

To address the study aims, two main analyses were run. First, to explore the interaction of bilingual experiences and age in a between groups manner, we ran generalized additive models (GAMs) using the *mgcv* package (Wood, 2017) in R (R Core Team, 2021). This was done as we wanted to account for any non-linear trajectory of neural decline over time. GAMs fit a nonlinear regression spline consisting of the sum of simpler nonlinear functions, but only where sufficient evidence exists for a specific curve. GAMs report the nonlinearity of an effect via a measure of estimated degrees of freedom (edf), where edf = 1 denotes a linear term and edf>1 indicates a nonlinear term. The GAM analysis was carried out on a matched bilingual and monolingual participant sample. In addition to the quality control metrics, sex and education level have been previously shown to ameliorate neurocognitive decline (Arenaza-Urquijo et al., 2017; Levine et al., 2021). The participant groups were thus matched on age, sex, education, baseline cognitive performance (ACE-III scores), average CNR, average SNR, and absolute motion in the scanner using the *MatchIt* package (Ho et al., 2011). We used optimal pair matching to create the dataset. As several of the factors used for matching were continuous, covariate balance was assessed using the *cobalt* package (Greifer, 2021). Covariate balance was optimal for all variables (adjusted variance ratios<2), apart from age (marginal, adjusted variance ratio = 2.4) and absolute motion (adjusted variance ratio = 3.5). The matched dataset consisted of N = 44 individuals (22 bilingual and 22 monolingual; Table 1). As covariate balance was sub-optimal for absolute motion and sex was a dichotomous variable, these were run as random smooths in the GAM analyses.

Separate GAMs were run for both whole-brain and ROIs in two sets of analyses. A first model examined the effects of age on WM integrity, both on the whole-brain level and in the specified ROIs. Two follow-up models were then run. The first added an interaction term of age by language group ('bilingual' and 'monolingual'), run as an ordered factor, to assess if the trajectory of age differed significantly between bilinguals and monolinguals. These models were run twice, first with the reference level set to monolingualism, and then with reference set to bilingualism. A third, final model was run only if the interaction of age and 'lingualism' was reliably significant in both versions of the second model, that is a significant interaction was observed with both bilingualism and monolingualism set as the reference level. This final model included the age by language group interaction but now modelled language group as an unordered factor. This was done to model specific effects of age separately per language group to tease apart the interaction from the previous model.

To examine how varying degrees of bilingual experience might ameliorate the trajectory of aging over time, the whole-brain and ROI WM values were submitted to a regression analysis with general linear models (GLM) using the *stats* package (R Core Team, 2021). Two models were run. A first, base model included terms of age, sex, education, CNR, SNR, and absolute motion in the scanner. A second model then added an interaction term of BCS with age and a main effect of BCS. Model fit was compared between the two using the anova function via the *stats* package. Only the models which significantly improved fit over the base model were followed up and reported in the results. To account for multiple comparisons in the GLM analysis, all p-values were thresholded at a bonferroni-corrected value of p = 0.00417.

3. Results

3.1. Aging trajectory analysis (GAM)

A significant effect of age was observed for all FA (decreases) and MD (increases) values across all ROIs apart from FA in the bilateral SLF. The second set of models ('lingualism' as an ordered factor) revealed three significant interactions. With bilingualism set as a reference, age by monolingualism interaction was significant for right SLF MD ($p = 0.042219$) and right SLF FA ($p = 0.00495$) measures. With monolingualism set as a reference, age by bilingualism interaction was significant for MD in the left SLF ($p = 0.0442$) and FA in the right SLF ($p = 0.00635$). Thus, the third-level analysis was run only on the right SLF FA.

Results from the third-level model on right SLF FA values (treating "lingualism" as an unordered factor) revealed a significant interaction of age and monolingualism ($p < 0.00786$; edf = 1.0002). This model also revealed a significant effect of sex ($p = 0.01184$) and absolute motion ($p = 0.02496$). See Fig. 1 for a summary visualization. The interaction between age and bilingualism in this model, however, was not significant.

3.2. Individual differences analysis (GLM)

The base model revealed a significant effect of age for most ROIs. This effect was found for whole brain FA and MD values, CC FA and MD values and MD values in the bilateral IFOF and the bilateral SLF. However, age did not significantly predict FA values in the SLF bilaterally. In the follow up analysis, adding BCS as a main effect and BCS by age interaction to the model, did improve model fit for all models except for the ones with FA values in the bilateral IFOF and bilateral SLF.

For the follow-up models which improved model fit, model summaries showed a significant interaction between age and BCS on whole brain FA and MD values, CC FA and MD values, left IFOF MD values, right IFOF FA and MD values, and bilateral SLF MD values (Table 2; Fig. 2). However, the significance level of the CC (FA and MD), right IFOF FA, and bilateral SLF MD did not survive correction for multiple comparisons.

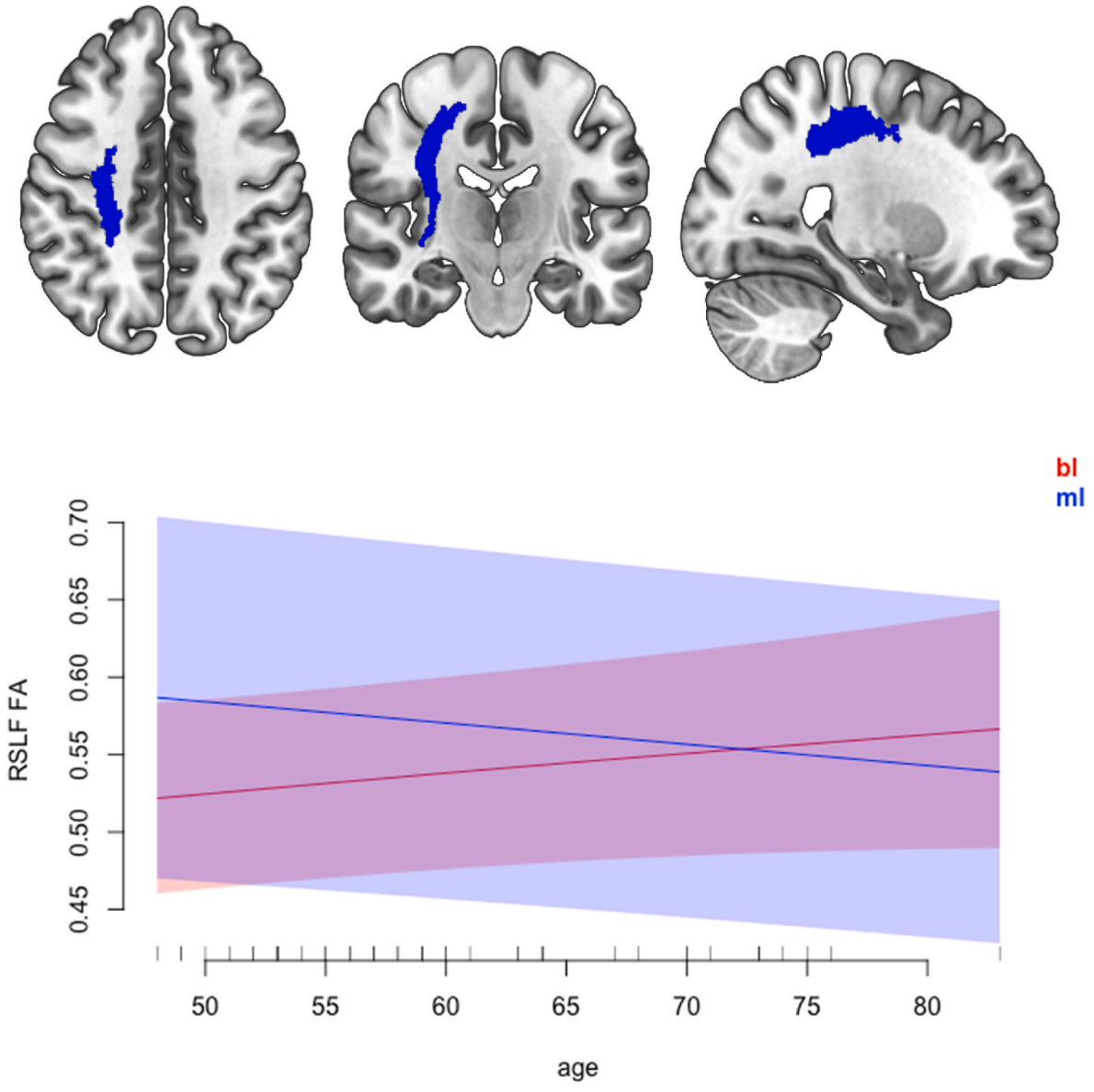

Fig. 1. Effect of age and language group interaction on the right SLF fractional anisotropy. See mask of the right SLF superimposed in blue on an MNI152 template in the upper panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Output from GLM analyses. Significance levels of age by BCS interaction are only reported for models where the addition of BCS improved goodness of fit over the base model. Bolding indicates significance after correction for multiple comparisons.

Brain region	White matter integrity measure	Significance level of the age × BCS interaction	T statistic
Whole brain	**FA**	**p = 0.00711**	**t = 2.774**
	MD	**p = 0.00208**	**t = −3.200**
Corpus callosum	FA	p = 0.01717	t = 2.442
	MD	p = 0.01003	t = −2.648
Left IFOF	**MD**	**p=0.000258**	**t=-3.854**
Right IFOF	**MD**	**p=0.001273**	**t=-3.360**
Left SLF	MD	p = 0.00468	t = −2.923
Right SLF	MD	p = 0.00564	t = −2.858

4. Discussion

The present study attempted to address two main issues. First, we aimed to examine how bilingualism modulates the trajectory of neural decline in normal aging. Second, we aimed to examine the extent to which the degree of bilingual engagement might ameliorate this trajectory across the adult lifespan. The results herein indicate that bilingualism, in at least certain tracts, modulates the trajectory of age-related decline in WM integrity. Furthermore, the degree of amelioration seems calibrated to the degree of bilingual engagement across the adult lifespan. The amelioration of WM trajectories seen in both analyses is in line with our predictions. Specifically, the negative effect of age on FA values for monolinguals in the right SLF, seen in the GAM analysis, indicates a typical degradation with age for monolinguals, reflected in faster WM integrity reduction. Across both whole-brain and specific tract ROIs in the GLM analysis, the degree of engagement with bilingual experience was found to modulate the slope of decline in WM integrity. These results indicate degree of engagement with bilingual experiences ameliorates the rate of decline across the lifespan. Specifically, a higher degree of engagement seems to correlate to a slower rate of decline. Taken together, this supports an account of bilingualism contributing to brain reserve (Abutalebi et al., 2015; Perani and Abutalebi, 2015).

Models of aging propose a shift in reliance from posterior to anterior structures in handling various cognitive demands (Davis et al., 2008), while the adaptations to bilingual language control demands have been proposed as a mechanism by which these fronto-posterior connections are maintained (Grant et al., 2014; Grundy et al., 2017). By nature of its design, the present study cannot adjudicate directionality of this shift. However, given that the SLF connects frontal, parietal, and posterior regions of the brain, the maintenance of WM integrity in bilinguals can be interpreted within these proposals as a measure of maintenance of these connections subsumed within the SLF. Specifically, the preservation of WM integrity in aging suggests a maintenance of the structural basis for efficient communication between a wider network of brain regions which can be plastically recruited to handle control demands more efficiently (Grundy et al., 2017; Hernandez et al., 2019; Pliatsikas, 2020).

The effect in the right SLF also partially overlaps with findings in younger adults showing bilingualism-induced plasticity in this region (Mamiya et al., 2016; Singh et al., 2018). Singh et al. (2018) report increased axial diffusivity values for bilinguals than monolinguals in this tract, which is interpreted as axonal restructuring for increased efficiency in communication between the regions it connects. Interestingly, a similar effect is observed in aging cohorts for the SLF (Anderson et al., 2018a). Compared to the results seen across younger and older populations, the difference in age trajectories for FA values observed between groups herein supports the interpretation of optimization of WM structure to handle communication most efficiently between connected

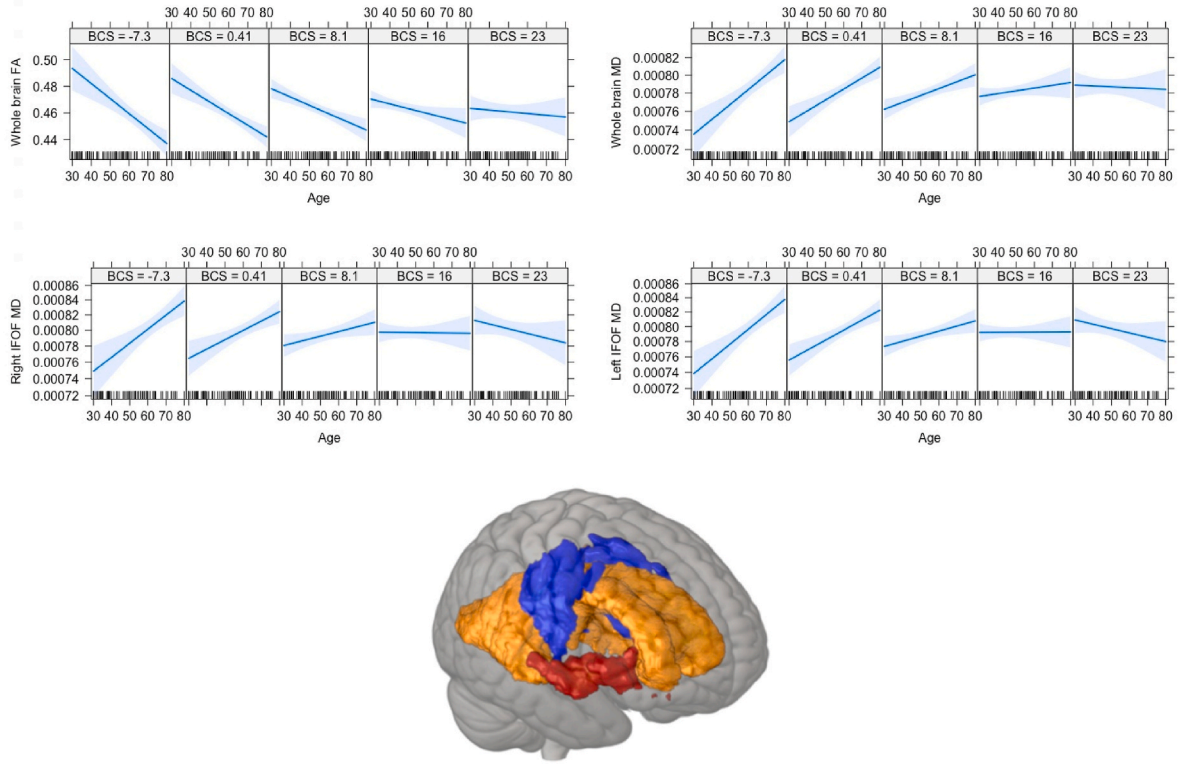

Fig. 2. Visualization of the significant age by BCS interaction effects at the Bonferroni-corrected significance level of p = 0.00417. A three-dimensional visualization of the masks used for extraction of WM data. Bilateral corpus callosum in orange; bilateral IFOF in red; bilateral SLF in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

regions which contributes to increased *resiliency* of WM to age-related degradation (Pliatsikas, 2020).

The trends from the individual differences analyses adds to results suggesting that the degree of preservation afforded by bilingualism-induced plasticity is calibrated to the degree of engagement with the experience (Voits et al., 2022). The interaction between increased bilingual engagement and age, as a flattening of the trajectory of decline, is indicative of increased WM structural preservation with more active engagement in bilingual experience. Akin to the findings for the first analysis discussed above, this interaction can be interpreted as an outcome of neurocognitive adaptations to peak efficiency; that is, not necessarily increased WM, but a restructuring towards optimal efficiency in communication between regions which provides a basis for resilience to age-related decline (Pliatsikas, 2020). A similar argument can be made for the effects seen in MD values within the right IFOF. Higher degrees of engagement would suggest the results of adaptation in WM microstructure to optimally and efficiently handle control demands (Abutalebi and Green, 2016). As the IFOF connects the frontal regions associated with cognitive control to other parietal and posterior networks, this indicates a prolonged use of the specific regions in a wider network to handle control demands, which in turn contributes to resilience to degradation within this tract. Whole-brain MD is an indicator of global brain health and increases with age (Rathee et al., 2016). The continuous use of this system throughout the later years of life ensures resilience of the brain structures and connections between them against neural atrophy associated with healthy aging and, possibly, dementia. A similar argument can be made for whole-brain FA (Kochunov et al., 2012).

Although we saw sensitivity of age by BCS interaction for most MD values in the whole-sample GLM analyses, this was not as widely applicable to FA values. However, this pattern of results is not necessarily unexpected. Recall that FA and MD tap into slightly different aspects of WM integrity. Furthermore, literature suggests that MD is more sensitive to aging than FA (Cox et al., 2016), and, as such, changes to it are more likely to manifest in middle age which is when the first signs of cognitive aging might emerge. Pertaining to the data herein, it follows that the more sensitive measures to early aging would also be more likely to be affected by bilingual experience. Indeed, our matched sample (older age) showed predominantly FA effects. It is, however, worth reiterating that in both FA and MD measures, bilingual engagement appears to correlate to better-maintained WM integrity through aging. It is possible that bilingual effects may simply manifest in different ways depending on participant age at testing, although further research in middle-aged through older populations is required to assess this claim.

The trends seen in the present data are also in line with previous literature showing preserved WM structure in aging (Luk et al., 2011; Anderson et al., 2018a). Specifically, it appears that the underlying structural basis for brain reserve seen is not necessarily 'more' WM but the preservation (resilience) of what is already present (Pliatsikas, 2020). It is worth noting that these results at face value seem to not align with more recent work (Anderson et al., 2021) showing bilinguals to have a *faster* decline in WM structure in aging. However, the discrepancy may be explainable as a function of age. The average age of the participants in the study by Anderson et al. (2021) was 10 years older than those in the matched sample within the present study. As alluded to earlier, it is predicted that with increasing age, there is a shift from greater neural resilience to a more compensatory mechanism with increasing age (see for discussion Bialystok, 2021). Under such a view, these results are simply capturing separate snapshots of an overarching shift in reserve mechanisms in aging. Recall that in both instances, the groups had been matched for cognitive performance. Thus, it is possible that the results from the present study represent an earlier, brain reserve mechanism (resilience to decay), while the results from the Anderson et al. (2021) study may be capturing a later, compensatory account where cognition is maintained in the face of structural decline. However, more research examining bilingual effects on the aging trajectory with a broader range of ages is needed to assess this interpretation.

Together, these results suggest that a more nuanced exploration of bilingual effects in aging is warranted and, indeed, is the ideal way to better unpack these in future. Previous studies have traditionally employed a monolingual vs bilingual cohort design, which shows group level differences in a single point in the aging process. While such study designs are absolutely warranted, we submit that future research examining potential bilingual effects would ideally also examine age as a trajectory and include continuous measures of bilingual experience.

While the present results are encouraging, it should be noted that the cohort-based study design such as the present study is not able to assess a causal link between bilingual experience and neurocognitive outcomes. We are examining trajectories by measuring brain adaptations at a single point in time for each individual across a larger age range, which delimits what can be measured regarding brain adaptations and language use patterns over time. Future research would also examine such patterns of neurocognitive aging from a longitudinal perspective. This would enable the examination of dynamic changes to brain structure through some portion of the aging process and allow us to better understand these against dynamic shifts in patterns of language use.

To conclude, bilingual experience is a factor in ameliorating the progression of neural decline via maintenance of neural circuits implicated in language- and executive control demands. Taken together, the results presented herein indicate that bilingualism contributes to a prolonged maintenance of existing WM integrity throughout the adult lifespan. Crucially, the degree of engagement in bilingual experience is also an explanatory variable: the greater engagement with bilingual experiences, the greater the effect on WM integrity preservation across the middle to older age lifespan.

Credit author statement

Vincent DeLuca: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft preparation, Writing- Reviewing and Editing **Toms Voits:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft preparation, Writing-Reviewing and Editing.

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