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Bilingualism and "brain reserve": a matter of age

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ABSTRACT

There is a lively debate whether bilingualism as a state of permanent cognitive control contributes to so-called *brain reserve*, thus delaying the onset of symptoms associated with neurodegeneration by up to 5 years. Here, we address this question in a large-scale (n = 399) population-based study. We compared the gray matter volume of monolinguals versus bilinguals in the left inferior frontal gyrus and inferior parietal lobule cortex and its modulation by biological age. Three core findings emerged: (1) Brain volume was systematically higher in bilinguals than monolinguals. (2) This difference disappeared at higher ages, and the slope of decline was steeper for bilinguals than monolinguals. (3) The volume difference between age groups disappeared in the inferior frontal gyrus at earlier ages than in the inferior parietal lobule. Thus, bilingualism might indeed contribute to brain reserve in older age, with posterior regions showing a particular resilience to atrophy and thus less necessity for functions to shift to anterior control regions.

1. Introduction

The course of aging is associated with cognitive decline, that is, progressive decrease of cognitive abilities associated with various age-related neurobiological changes, such as structural atrophy (Raz et al., 2005; Whalley et al., 2004). Interestingly, a substantial proportion of seniors can tolerate greater amounts of neurodegeneration than others without obvious cognitive impairments (cf. Valenzuela and Sachdev, 2006). The neural mechanism behind this phenomenon is termed "neural/brain reserve" (for reviews, see Abutalebi and Green, 2016; Bartres-Faz and Arenaza-Urquijo, 2011; Guzman-Velez and Tranel, 2015; Perani and Abutalebi, 2015; Pliatsikas, 2019). Brain reserve is modulated, for example, by an upregulation of noradrenaline, which in turn facilitates neurogenesis, synaptogenesis, and cortical connectivity (cf., Guzmán-Vélez and Tranel, 2015; Robertson, 2013).

One prominent factor among the resources of "reserve" is bilingualism or multilingualism. Bilingual or multilingual participants acquire more than one language simultaneously or successively and are thus required to exert constant control over different rules and vocabularies of more than one language and the appropriate switching or staying (Byalistok, 1991; Green and Abutalebi, 2013). There is an ongoing debate whether bilingualism is indeed a relevant factor for "brain reserve," providing neuroprotection and thus delaying cognitive decline and even the onset of dementia by up to five years (Abutalebi et al., 2015; Alladi et al., 2013; Bialystok et al., 2007; Craik et al., 2010; Gold, 2015; Gold et al., 2013; Perani et al., 2017; Pliatsikas et al., 2015; see also Bak, 2016). Not only early bilingualism but even the acquisition of a second language in school (9–17 years of age) or even later in adulthood was found to have a positive effect on cognitive abilities later in life (Bak et al., 2014; Waldie et al., 2009). Other studies, however, failed to obtain supporting evidence (Crane et al., 2009; Lawton et al., 2015; Sanders et al., 2012) or argued that the general level of education was an important confound (Gollan et al., 2011), which is often, but not necessarily always, positively correlated with bilingualism.

In neuroimaging, differences between monolinguals and bilinguals have been reported for various different measures: gray matter volume (GMV), gray matter density, cortical thickness, and

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white matter integrity in regions associated with language and executive functions. In the language domain, effects were observed in particular in the left inferior frontal gyrus (IFG) and inferior parietal lobule (IPL) (Li et al., 2014; Stein et al., 2014). In the domain of cognitive control, bilinguals appear to have higher GMV in the right IFG, the anterior cingulate cortex and the basal ganglia (Abutalebi et al., 2013, 2015). In their comprehensive literature review, Abutalebi and Green (2016) juxtapose the roles of the left and right IFG and argue that the left IFG is likely involved in the selection of the appropriate response (i.e., lexical retrieval), whereas the right IFG is more involved in response inhibition (i.e., blocking lexical competitors in the other language). Based on the presently available literature, Grundy et al. (2017) formulated the "bilingual anterior-to-posterior and subcortical shift" model, which conceptualizes more efficient information processing in the bilingual brain by the preferential involvement of posterior instead of anterior brain regions. Most recently, Pliatsikas (2019) summarized the evidence available to-date and integrated it into his "dynamic restructuring model". This model differentiates the impact of bilingual exposure into the three phases: *initial exposure, consolidation, and peak efficiency*, during which differential effects can be seen on cortical gray matter (among them IPL for language and IFG for cognitive control), subcortical gray matter (also counting the cerebellum), and white matter tracts in terms of an optimization from local cortical to global hardwired processing.

Most studies in the literature investigated younger adults (Martensson et al., 2012: average ca. 20 ± 2 years; Stein et al., 2012: average 17.5 years, range 16.0–18.5 years), not addressing neuroprotection in older age (as one large-sample exception in the behavioral domain, the study by Kavé et al., 2008, with n = 814 should be mentioned). Moreover, even if older samples were considered (e.g., Abutalebi et al., 2015), small sample sizes were often potential limitations (in the domain of brain perfusion, one notable exception is the positron emission tomography study by Perani et al., 2017, with n = 85 patients with Alzheimer, 45 bilinguals and 40 monolinguals). Thus, despite the somewhat conclusive evidence (as reviewed, e.g., by Grundy et al., 2017), it is not yet entirely clear to what extent bilingualism systematically impacts on GMV and its constituents (cortical thickness [CT] and surface area [SA]) and how far this influence diminishes at older ages.

Therefore, we devised a population-based, large-sample study investigating the influence of bilingualism on GMV in atlas-defined language-relevant brain areas to test the notion of *brain reserve*. GMV obtained from monolingual and from multilingual participants were acquired from regions of interest (ROIs) in Broca's region (Amunts et al., 1999) and the IPL (Caspers et al., 2006, 2008) in the left hemisphere. The rationale of the analysis was as follows: 1) Investigation of the overall effect of *bilingualism versus monolingualism* on GMV in the two literature-based ROIs. 2) Inclusion of *age* as a potentially confounding variable into the analysis to investigate differential age effects on monolinguals and bilinguals. 3) Insight into the specific effect of bilingualism versus the general level of education. Moreover, to test whether the specific and hypothesis-driven effects observed in the ROIs were also present in other brain regions reported in the literature, a subsequent ROI analysis for the right IFG involved in global control (response inhibition, cf. Abutalebi and Green, 2016) was computed to complete the picture. Owing to the differential roles of the left and right IFG in the exertion of local or global control and their functions in the selection versus inhibition of responses, one may speculate that the patterns of results could differ for these two ROIs.

2. Methods

All methods were approved by the Local Ethics Committee of the University of Duisburg-Essen. The study was conducted in compliance with the Declaration of Helsinki. Informed consent was obtained from all participants.

2.1. Participants

The current sample is based on an existing cohort of 1201 participants (Sample size at the time of the onset of data analysis, February 2016. The cohort now comprises 1316 participants as of February 2018) recruited by the 1000BRAINS study (Caspers et al., 2014). 1000BRAINS is a population-based cohort study, which investigates the interindividual variability in brain aging. The cohort of 1000BRAINS is recruited from a sample of the Heinz Nixdorf Recall study and the associated MultiGeneration study, involving the spouses and offspring of the Heinz Nixdorf Recall study participants (Erbel et al., 2012; Schmermund et al., 2002), including healthy citizens from the towns of Essen, Bochum, and Mülheim (Germany), aged 18–87 years. Owing to its nature as a population-based study, the only exclusion criteria for 1000BRAINS were contraindications for the MR session: coronary artery stents, cardiac pacemakers or surgical implants or prostheses in the trunk or head, claustrophobia, a history of neurosurgery, and the presence of tattoos or permanent make-up on the head.

Participants were then considered for the present study if they had completed the *Language Experience and Proficiency Questionnaire* (LEAP-Q; Marian et al., 2007; see below), had obtained assessment of their International Standard Classification of Education level (UNESCO Institute for Statistics, 2012), and had a structural MRI data set of sufficient quality (n = 678). Based on the LEAP-Q data, further exclusion criteria were defined: simultaneous bilingualism (9 participants; the few bilingual participants with simultaneous acquisition were excluded because of reports in the literature about substantial neurofunctional and neurostructrual differences between them and successive bilinguals; for reviews cf. Berken et al., 2017; Klein et al., 2014: There were no, or reduced, differences between simultaneous bilinguals and monolinguals, whereas the well-known differences could be observed for successive bilinguals), developmental first language deficiencies in any modality (speaking, comprehending, reading, writing) (65 participants), and left-handedness (12 participants). Moreover, participants for whom the transformation of their anatomical data set to the template was not possible were excluded (104 participants, most due to motion artifacts, some because of macroanatomical deviations so huge that they could not be processed by the algorithm). With the exclusion of 59 participants after outlier correction (values for CT, SA, and/or GMV exceeding 3 standard deviations from the mean, respectively), and further exclusion of 3 participants who were each biologically related to one other study participant, subsequently a total of 224 monolinguals and 175 bilinguals constituted the sample of this study (Table 1).

2.2. Assessment of bilingualism (LEAP-Q)

To assess information about participants' second language status, the LEAP-Q was consulted. LEAP-Q is a reliable and valid instrument to determine language profiles of neurologically healthy bilingual and multilingual adults. In a self-assessment, participants are requested to list and rate their second language(s), including the age of acquisition, proficiency of all modalities, and manner of acquisition. For the purpose of the current study, the LEAP-Q was used to classify participants into two groups: monolinguals and bilinguals. Participants who were presently able to speak, understand, read, or write in at least one more language other than the mother tongue were classified as bilinguals. In turn, participants with no or lost second-language abilities were classified as

Table 1
Analysis of regions of interest in the left hemisphere

	Monolingual (n = 224)			Bilingual (n = 175)		
	Total (n = 399)	Younger (<64.5 y)	Older (>64.5 y)	Total	Younger (<64.5 y)	Older (>64.5 y)
Gender						
% Female	52.7	63.6	45.6	48.6	50.0	46.0
% Male	47.3	36.4	54.4	51.4	50.0	54.0
Age (years)						
Mean (SD)	66.5 (8.9)	58.4 (7.7)	71.7 (4.8)	58.0 (12.96)	51.0 (10.8)	70.3 (4.3)
Minimum	25.8	25.8	64.5	26.0	26.0	64.5
Maximum	84.2	64.5	84.2	82.5	64.5	82.5
Education level (SD)	5.5 (1.7)	5.8 (1.7)	5.4 (1.6)	7.5 (1.9)	7.3 (1.8)	7.7 (1.9)

Group characteristics for the monolingual and bilingual participants reported for the entire sample and for the younger (below median) and older (above median) participants.

monolinguals. Of the bilinguals, only 7 stated that they had no present exposure to their second language. All other indicated that they used their L2 *always* (n = 10), *frequently* (n = 25), *sometimes* (n = 57), or at least *rarely* (n = 18) in the context of friends or family, speech lab, reading, TV, or radio. Because the according LEAP-Q scale of present L2 exposure does not include exposure over previous years, we refrained from using these values as covariates in the subsequent analyses.

2.3. MRI data

2.3.1. Data acquisition

MRI sequences were acquired using a 3T Siemens (Erlangen) Tim-TRIO MR scanner. For each participant, 3D high-resolution T1-weighted magnetization-prepared rapid acquisition gradient-echo (MPRAGE) scans were acquired, using a 32-channel head coil (176 slices, slice thickness 1 mm, repetition time = 2250 ms, echo time = 3.03 ms, field of view = 256 × 256 mm^2, flip angle = 9°, voxel resolution = 1 × 1 × 1 mm^3).

2.3.2. Image processing

As a first preprocessing step, T1-weighted data of all participants were skull-stripped and segmented into gray matter, white matter, and cerebrospinal fluid using SPM8 (www.fil.ion.ucl.ac.uk/spm). Gray and white matter masks were summed up to provide a robust and accurate brain mask, which was entered into subsequent preprocessing steps for surface reconstruction. Cortical reconstruction was then carried out using the standard pipeline implemented in FreeSurfer 5.3 (http://freesurfer.net). After transformation to Talairach space, gray matter and white matter were segmented, gray and white matter boundaries were tessellated, and topological defects were corrected. Finally, for each subject, surface maps were generated, for example, CT, pial SA, and GMV. For ROI-based analyses, surface-based parameters including the pial SA and CT were extracted from the preprocessed data within the predefined cytoarchitectonic areas of the IFG and IPL. GMV was captured for each cytoarchitectonic area (IFG: areas 44 and 45 [Amunts et al., 1999]; IPL: areas PF, PFcm, PFm, PFop, PFt, PGa, and PGp [Caspers et al., 2006]) by multiplying CT with SA (Panizzon et al., 2009). Total IFG and IPL volumes were generated as the sum of the associated cytoarchitectonic GMV values, which subsequently represented our ROI values. An outlier correction was conducted for all relevant surface-based parameters, including SA, CT, and GMV. For the location of the anatomical ROIs, cf. Fig. 1. In addition, we also report analyses on the SA and CT values to provide a broader picture of the sources of the observed GMV effects (for details about the statistical analyses, please see below). Finally, CT and SA were also assessed for the right IFG, and the corresponding GMV was computed accordingly.

2.4. Statistical analysis

2.4.1. MANOVA models for the ROIs

2.4.1.1. Basic model. For the main research question of cortical differences between monolingual and bilingual participants, GMV values for left IFG and IPL were submitted to a multivariate analysis of variance (MANOVA) with *language group* as a between-subject factor. The same analysis was rerun for SA and CT of the left IFG and IPL instead of GMV.

2.4.1.2. Refined model. Next, the same analysis was extended into a MANCOVA by adding *age* as a continuous covariate into the model. Given the significant effect of this covariate, the sample was split at the age median (64.5 years) and *age group* was now added as an additional factor, rather than as a nuisance covariate, into the MANOVA model, turning it into a 2 × 2 MANOVA with factors *language group* (monolingual/bilingual) and *age group* (younger/older). Pairwise contrasts were assessed for each of the two age groups, thus comparing younger and older participants separately for the influence of bilingualism on their GMV. Finally, as a control analysis, this procedure was repeated after splitting the sample further into four age quartiles (at ages 58.8 years, 64.5 years, and 70.5 years) instead of two age groups, thus creating a new factor *age group* with four levels. The same analysis was rerun for SA and CT of the left IFG and IPL instead of GMV.

2.4.2. Demographic differences between subgroups

To identify further variables with potentially systematic influence on the group differences, we assessed whether the monolingual versus bilingual participants were comparable with respect

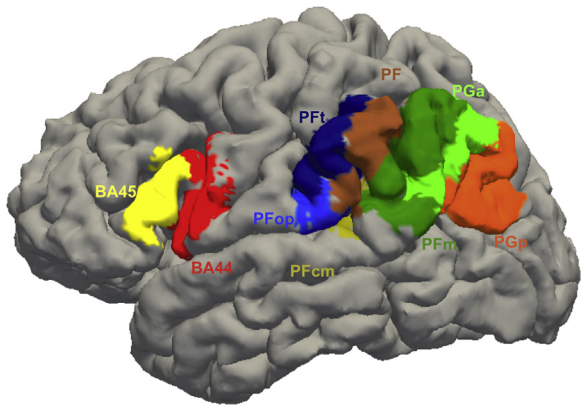

Fig. 1. Shape and position of the frontal and parietal ROIs in the left hemisphere. The areas were obtained from the JuBrain probabilistic cytoarchitectonic brain atlas. Frontal areas 44 and 45 formed the IFG ROI, areas PF, PFt, PFop, PFcm, and PFm in the supramarginal gyrus and areas PGa and PGp in the angular gyrus the IPL ROI. Abbreviations: IFG, inferior frontal gyrus; IPL, inferior parietal lobule; ROI, region of interest.

Table 2
Analysis of regions of interest in the right hemisphere

	Monolingual (n = 223)			Bilingual (n = 171)		
	Total (n = 394)	Younger (<64.5 y)	Older (>64.5 y)	Total	Younger (<64.5 y)	Older(>64.5 y)
Gender						
% Female	52.9	63.6	45.9	48.5	50.5	46.6
% Male	47.1	36.4	54.1	51.5	49.5	53.2
Age (years)						
Mean (SD)	66.4 (8.9)	58.4 (7.7)	71.7 (4.8)	58.2 (13.0)	51.2 (10.9)	70.3 (4.3)
Minimum	25.8	25.8	64.5	26.0	26.0	64.5
Maximum	84.2	64.5	84.2	82.5	64.5	82.5
Education level (SD)	5.5 (1.7)	5.8 (1.7)	5.4 (1.6)	7.5 (1.9)	7.4 (1.8)	7.7 (1.9)

Note that hemispheres were processed separately. For some participants, the anatomical data sets for the right hemisphere could not be normalized to the template with sufficient accuracy. Therefore, for the right hemisphere, only 394 valid data sets were available. For details, cf. Table 1.

to their *age* (independent-samples *t*-test) and the potentially relevant factor *education* (independent-samples *t*-test for education in years). These results, together with the insights from the MANOVA models, served as the basis for the subsequent correlation analyses, which treated the influencing factors as continuous variables. The same analysis was rerun separately for SA and CT.

2.4.3. Correlation analyses

2.4.3.1. Basic model. Given the different effects of bilingualism on GMV in younger versus older participants, the influence of age on GMV in each of the two age groups was assessed with Pearson's correlation. The ensuing coefficients for both groups were then converted into Fisher's Z values and compared statistically (formulas from Cohen et al., 2003). The same analysis was rerun for SA and CT.

2.4.3.2. Refined model. Given the significant group differences between monolinguals and bilinguals with respect to both *age* and *education*, these two variables were considered in the next step as potential nuisance variables into the correlation analysis to partial out their influence on the GMV differences of monolinguals versus bilinguals. Because *age* was at the same time a variable of interest, it could not be treated as a nuisance variable in the classic way. Instead, we corrected for the different average age levels of the monolingual and bilingual participants by subtracting the respective group mean from each individual age values for each subject. Thus, if the differential age distribution in the two groups had an influence on the slopes of the regression lines, the slopes would be corrected accordingly, thus removing any spurious differences between the correlation coefficients. Moreover, owing to the potential influence of *level of proficiency* and *age of acquisition* of the second language on the correlation coefficients in the bilingual group, those two variables were additionally included as nuisance variables in the correlation model for the bilinguals (note that these variables are by definition not available for the monolinguals). The resulting, thus, corrected correlation coefficients were again converted into Fisher's Z values and then compared statistically. The same analysis was rerun for SA and CT.

2.4.4. Analysis of the right IFG as a control region

Finally, the analyses for the right IFG were conducted in the same order and logic as those for the left IFG, with two small exceptions: (1) The GMV for the two hemispheres were calculated separately. For some participants, the anatomical data sets for the right hemisphere could not be normalized to the template with sufficient accuracy. Therefore, for the right hemisphere, only 394 valid data sets were available (cf. Table 2 for a description of the demographics). (2) For the left hemisphere, both ROIs were considered simultaneously as dependent variables in the analysis. For the right hemisphere, only one ROI was present.

3. Results

3.1. MANOVA models for the ROIs

3.1.1. Analyses for GMV

3.1.1.1. Basic model. In both ROIs of the left hemisphere, the GMV was significantly higher for bilinguals than for monolinguals (MANOVA: IFG: $F[1, 396] = 7.522$; $p = 0.006$; IPL: $F[1, 396] = 22.708$; $p < 0.001$; Fig. 1).

3.1.1.2. Refined model. Adding *age* as a covariate into the model revealed that it had a significant effect on the GMV in both ROIs (IFG:

Table 3
Results for the separate (M)ANOVA models for CT and SA done analogously to the analyses for GMV for the ROIs in the left hemisphere

	Basic model	Refined model	
	Language group	Language group	Age group
Main Effects GMV	$F[1, 396] = 11.782$ ***	$F[1, 394] = 4.916$ **	$F[1, 394] = 33.997$ ***
Left IFG	$F[1, 396] = 07.522$ **	$F[1, 394] = 1.185$	$F[1, 394] = 43.925$ ***
Left IPL	$F[1, 396] = 22.708$ ***	$F[[1, 394] = 9.849$ **	$F[1, 394] = 46.116$ ***
Main Effects SA	$F[1, 394] = 06.249$ ***	$F[[1, 392] = 2.684$ *	$F[1, 392] = 23.004$ ***
Left IFG	$F[1, 394] = 04.684$ *	$F[1, 392] = 0.601$	$F[1, 392] = 28.730$ ***
Left IPL	$F[1, 394] = 14.799$ ***	$F[1, 392] = 7.371$ **	$F[1, 392] = 18.386$ ***
CT			
Left IFG	$F[1, 394] = 02.457$	$F[1, 392] = 0.052$	$F[1, 392] = 28.174$ ***
Left IPL	$F[1, 394] = 05.444$ *	$F[1, 392] = 0.822$	$F[1, 392] = 32.060$ ***

For the sake of comparison, the GMV analyses are reported as well.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.
Key: CT, cortical thickness; SA, surface area; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; GMV, gray matter volume; MANOVA, multivariate analysis of variance; ROI, region of interest.

Table 4
Results for the separate *t*-tests for CT and SA done analogously to the analyses for GMV in the left hemisphere

ROI	Variable	Younger (<64.5 y)	Older (>64.5 y)
Left IFG	GMV	$t[198] = -2.158$ *	$t[197] = -0.687$
	SA	$t[198] = -1.947$	$t[198] = 0.932$
	CT	$t[198] = -0.725$	$t[198] = 0.401$
Left IPL	GMV	$t[198] = -3.278$ **	$t[197] = -1.248$
	SA	$t[198] = -2.693$ **	$t[198] = -1.299$
	CT	$t[198] = -1.475$	$t[198] = 0.102$

For the sake of comparison, the GMV analyses are reported as well.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$
Key: CT, cortical thickness; SA, surface area; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; GMV, gray matter volume; MANOVA, multivariate analysis of variance; ROI, region of interest.

$F[1, 395] = 65.259$; $p < 0.001$; IPL: $F[1, 395] = 67.491$; $p < 0.001$). Accordingly, by splitting the sample into an older and a younger group by the age median (64.5 years) and rerunning the analysis as a 2 × 2 MANOVA for the volumes of IFG and IPL with factors *language group* (bilingual vs. monolinguals) and *age group* (younger vs. older) revealed significant main effects of *language group* ($F[2, 394] = 4.916$; $p = 0.008$) and *age group* ($F[2, 394] = 33.997$; $p < 0.001$). Subsequent pair-wise contrasts of bilinguals versus monolinguals separately for each age group and ROI revealed significantly higher GMV in both ROIs for the group of younger participants (IFG: $t[198] = -2.158$; $p = 0.032$ one-tailed; IPL: $t[198] = -3.278$; $p = 0.001$ one-tailed), but not for the older participants (IFG: $t[197] = -0.687$; $p = 0.493$; IPL: $t[197] = -1.248$; $p = 0.213$; *p*-values Bonferroni-corrected for multiple comparisons within each group).

Breaking down the two age groups into four age quartiles further elucidated that the GMV differences were driven by the younger participants (group 1—IFG: $p = 0.033$; IPL: $p = 0.023$; group 2—IFG: $p = 0.356$; IPL: $p = 0.405$; group 3—IFG: $p = 0.073$; IPL: $p = 0.211$; group 4: IFG: $p = 0.438$; IPL: $p = 0.151$; all one-tailed).

3.1.2. Analyses for SA and CT

The results of the parallel analyses for SA and CT values are provided in Tables 3 and 4. Generally, across all analyses, it becomes evident that the significant group differences in GMV (i.e., the product of SA × CT) between monolingual and bilingual participants are mainly due to differences in SA, not CT.

3.2. Correlation analyses for the ROIs

3.2.1. Analyses for GMV

The findings above suggested a strong modulation of the GMV differences between *language groups* by biological *age*. Consequently, to gain insight into the development of GMV over the life span, separate correlation analyses for the monolingual versus bilingual participants with the variables *age* and *GMV* were conducted and compared using Fisher's Z. These analyses revealed significant negative correlations in both *language groups* and ROIs (Fig. 2). The negative coefficients of the correlation of *age* and *GMV* were significantly stronger for the bilingual (IFG: $r = -0.489$; IPL: $r = -0.471$) than those for the monolingual (IFG: $r = -0.252$; IPL: $r = -0.283$) participants (comparison for the IFG: $Z = 2.735$; $p = 0.006$; IPL: $Z = 2.174$; $p = 0.029$).

Next, to test the specificity of the influence of active bilingualism as compared with an unspecific effect of level of education (Gollan et al., 2011), an additional analysis was conducted. *Education* was added as a covariate into the correlation analyses described previously. This novel analysis yielded partial correlations of $r_{Monolingual} = -0.242$ versus $r_{Bilingual} = -0.490$ for the IFG and $r_{Monolingual} = -0.288$ versus $r_{Bilingual} = -0.477$ for the IPL. Like in the original analysis, these coefficients differed significantly (IFG: $Z = 2.853$; $p = 0.004$; IPL: $Z = 2.197$; $p = 0.028$), with steeper slope for the bilinguals.

Finally, when correcting the continuous variable *age* for the mean differences in age between the monolingual and bilingual group as described previously and including *level of proficiency* and

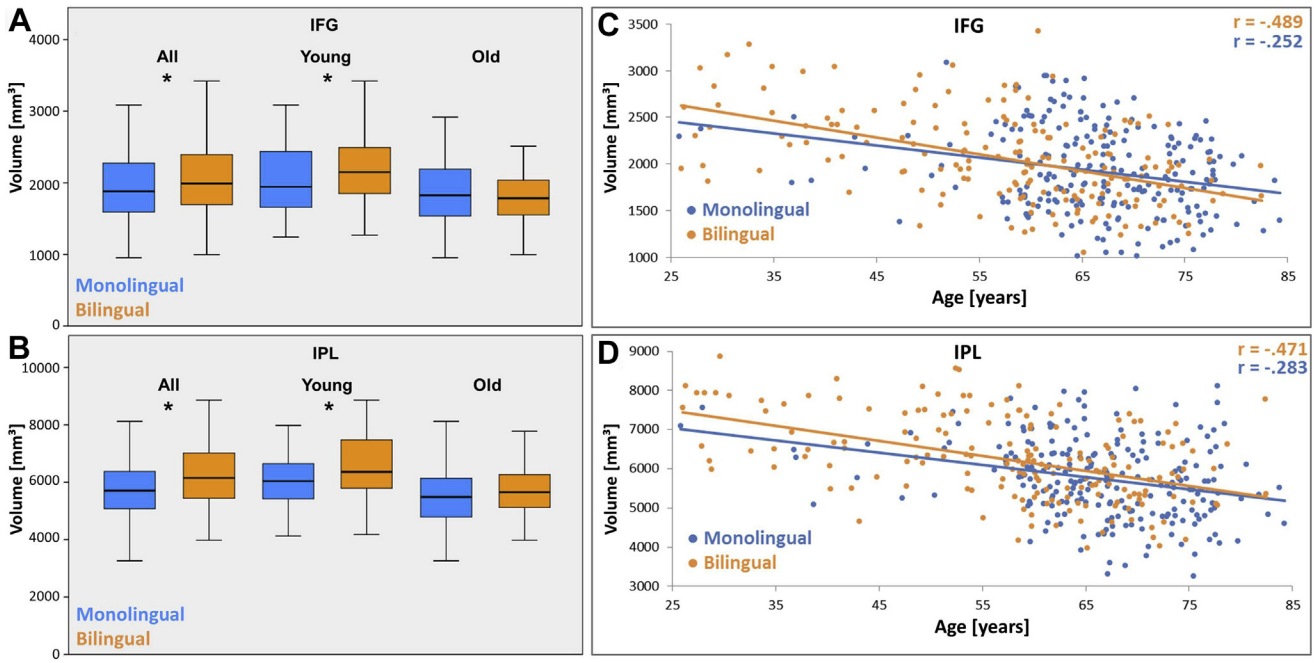

Fig. 2. Differences in the volume of the left IFG and IPL between bilinguals and monolinguals are modulated by age. There is an overall larger volume for bilingual than monolingual participants in the IFG (A) and IPL (B). However, this effect is only driven by the younger, not the older participants. The volumes in IFG (C) and IPL (D) decrease with age, at a faster rate for bilinguals than monolinguals. Thus, the volume difference vanishes early, at around 60 years, in the IFG (C), but only later, at around 80 years, in the IPL (D). Abbreviations: IFG, inferior frontal gyrus; IPL, inferior parietal lobule.

Table 5
Results for the separate correlation analyses for CT and SA done for the ROIs in the left hemisphere analogously to the analyses for GMV

	Age			Age (cov: Education)			Normalized age (cov: Education, AoA, Profi)		
	Mono	Bi	Fisher's Z	Mono	Bi	Fisher's Z	Mono	Bi	Fisher's Z
IFG									
GMV	−0.252	−0.490	2735 **	−0.241	−0.490	2853 **	−0.241	−0.485	2448 **
SA	−0.151	−0.353	2131**	−0.138	−0.352	2251 **	−0.138	−0.354	2273 **
CT	−0.335	−0.496	1577**	−0.357	−0.496	1677 **	−0.357	−0.489	1586 **
IPL									
GMV	−0.283	−0.470	2174**	−0.259	−0.473	2197 **	−0.259	−0.457	2247 **
SA	−0.141	−0.268	1306**	−0.108	−0.268	1635 **	−0.108	−0.249	1435 **
CT	−0,36	−0.499	1683**	−0.385	−0.500	1410 **	−0.385	−0.498	1384 **

For the sake of comparison, the GMV analyses are reported as well.
Significance of Fisher's *Z*: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.
Key: Mono, monolinguals; Bi, bilinguals; CT, cortical thickness; SA, surface area; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; GMV, gray matter volume; MANOVA, multivariate analysis of variance; ROI, region of interest; AoA, age of acquisition.

age of acquisition of the second language as nuisance variables for the bilingual group, the same pattern of results emerged with slight numerical differences. The negative coefficients of the correlation of *age* and *GMV* were significantly stronger for the bilingual (IFG: $r = -0.485$; IPL: $r = -0.457$) than those for the monolingual (IFG: $r = -0.241$; IPL: $r = -0.259$) participants (comparison for the IFG: $Z = 2.448$; $p = 0.014$; IPL: $Z = 2.247$; $p = 0.025$).

3.2.2. Analyses for SA and CT

The results of the parallel analyses for SA and CT values are provided in Table 5. All variables are correlated with age.

3.3. Analysis for the right IFG as a control region

The results of the analogous analyses for the right IFG as a control region in the right hemisphere are reported in Tables 6–8. Whereas the pattern of results in the MANCOVAs is comparable to that for the left IFG and IPL (i.e., effects in SA, but not in CT), the correlation coefficients for the decline of GMV, CT, and SA did not differ significantly between the monolingual and bilingual participants in any variant of the analysis (all *p*'s > 0.05 even when uncorrected for multiple comparisons). For GMV, the values for the three analyses were $p_1 = 0.159$; $p_2 = 0.115$; $p_3 = 0.149$, respectively.

4. Discussion

Investigating the GMV modulation in the left hemisphere by bilingualism as a function of biological age in almost 400 participants provided a novel perspective on the supposed neuroprotective function of bilingualism. (1) Overall, *bilinguals have higher* GMV in the left IFG and left IPL than monolinguals. (2) *Age* has a modulating influence on these differences: The higher GMV is only present in younger ages. In bilinguals, the rate of decline back to a GMV level comparable with that of monolinguals is consequently higher, that is, the slope is *steeper* in bilinguals. (3) This differential trajectory for bilingual versus monolingual participants was not observed in the right IFG, although all other effects from the left hemisphere were also found. (4) The in-depth analysis of GMV and its two factors SA and CT revealed that SA explains more differences between monolingual and bilingual persons than CT, in particular, in the IPL. However, the combination of both, that is, GMV, tends to explain the differences best.

Based on the cross-sectional data analyzed here, an attempt at a schematic longitudinal perspective is sketched in Fig. 3. This schematic model incorporates these data and the fact that language learning has an immediate effect on GMV (Martensson et al., 2012; Stein et al., 2012). According to this speculative model, the GMV in the left IFG and IPL increases by the time a second language is learned. Influential factors discussed in the literature are stimulation of neurotrophic factors (e.g., noradrenaline; cf. Guzmán-Vélez and Tranel, 2015; Robertson, 2013) and angiogenesis and synaptogenesis (Gold, 2015). Then, during the course of aging, the overall GMV declines again in both monolinguals and bilinguals. The rate of this decrease appears more pronounced for bilinguals, thus slowly reducing the earlier GMV difference. In terms of *brain reserve*, the findings of the present study indicate that bilingualism may indeed be advantageous—in particular for younger participants for whom the GMV difference is still more pronounced. For neurodegeneration in the IFG, the intersection of the trend lines in Fig. 2 suggests potential neuroprotection by bilingualism only in younger ages. For posterior atrophy (e.g., in the IPL), the relative difference may even persist up to 80 years or older (Fig. 2). In other words, the older a bilingual person is, the more may bilingualism have a relative protective effect on posterior rather than anterior parts of the language network.

The data presented here are compatible with two recently published accounts, which will be presented briefly. The "bilingual anterior-to-posterior and subcortical shift" model (Grundy et al., 2017) states that bilinguals recruit posterior (and also subcortical) regions to a higher extent than monolinguals, thus not relying too strongly on frontal regions associated with cognitive control. In contrast, in monolinguals, usually the "posterior-to-anterior shift in

Table 6
Results for the separate (M)ANOVA models for GMV, CT, and SA done analogously to the analyses for GMV for the ROI in the right hemisphere

Variable	ROI	Basic model	Refined model	
		Language group	Language group	Age group
GMV	Right IFG	$F[1, 392] = 13.391$ ***	$F[1, 390] = 6.026$ *	$F[1, 390] = 21.805$ ***
Main Effects		$F[2, 391] = 6719$ **	$F[2, 389] = 3.440$ *	$F[2, 389] = 15.767$ ***
SA	Right IFG	$F[1, 392] = 12.583$ ***	$F[1, 390] = 6.894$ **	$F[1, 390] = 11.287$ ***
CT	Right IFG	$F[1, 392] = 0.080$	$F[1, 390] = 0.395$	$F[1, 390] = 13.418$ ***

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.
Key: CT, cortical thickness; SA, surface area; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; GMV, gray matter volume; MANOVA, multivariate analysis of variance; ROI, region of interest.

Table 7
Results for the separate *t*-tests for GMV, CT, and SA done analogously to the analyses for GMV in the left hemisphere

	Younger (<64.5 y)	Older (>64.5 y)
Left IFG		
GMV	$t[195] = -2.650$ **	$t[195] = -0.763$
SA	$t[195] = -2.624$ **	$t[195] = -1.083$
CT	$t[195] = 0.076$	$t[195] = 0.789$

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.
Key: CT, cortical thickness; SA, surface area; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; GMV, gray matter volume; MANOVA, multivariate analysis of variance; ROI, region of interest.

aging" is observed, taken to reflect that frontal regions supporting controlled processing take over from posterior regions more associated with automatized processing (Davis et al., 2008; Turner and Spreng, 2012). Thus, the present data and model add a potential explanation why the observed posterior shift in bilinguals is beneficial: The increased GMV in bilinguals is present until higher ages in posterior as compared with anterior brain regions, thus maximizing the "reserve" effect. The effects in left frontal and parietal regions indicate the more rapid decline of the initial higher GMV in bilinguals with age. The two ROI analyses of the left IFG and IPL reveals that, although a diminishing of the higher GMV in bilinguals over time is present, this decline becomes effective much later in the IPL (intersection point of the two lines at about age 80 years) than in the IFG (intersection point at about age 55). Interestingly, regions for the exertion of global, domain-general control (in the present study the exemplary right IFG) seem to behave differently in the sense that the brain reserve here is even more persistent: The relatively higher GMV in bilinguals persists after the age of 55 (at which it disappears in the left IFG). This finding might be interpreted such that individual lexical selection in particular circumstances is not as helpful in terms of neuroprotection, or reserve, as the more general ability of bilingual persons to suppress irrelevant information (for differences between linguistic vs. nonlinguistic contexts and affordances cf. Weissberger et al., 2015). In other words, whereas increased reserve associated with bilingualism fades in actual language areas with age, it keeps adding a reserve in the nonlinguistic domain (for the interaction of other nonlinguistic functions such as attention with brain activation during language processing cf. Heim et al., 2010a, b).

The presented data and model are also in very close correspondence with Pliatsikas (2019) recent "dynamic restructuring model." As stated previously, this model, which was based on the evidence in the literature rather than own empirical data, basically assumes that initial exposure to another language leads to GMV increases in brain regions relevant for language and cognitive control (among them IFG and IPL). This increase in cortical GMV is then followed by increases in subcortical GMV and white matter tracts, that is, the hard-wiring of these regions takes place during consolidation. With this hard-wiring done, the cortical GMV effects

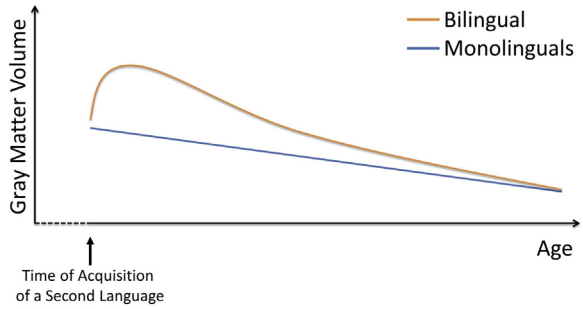

Fig. 3. A model of the development of brain volume in left-hemisphere language areas in bilinguals versus monolinguals. Exposure to more than one language leads to increase in the gray matter volume in bilingual participants close to the time of acquisition. Later in life, the volume decreases again until the difference between monolingual and bilingual participants disappears.

decline to their initial values because processing efficiency is now secured by the entire network architecture. It is exactly this pattern that we see here in our empirical data over the life span. Further work will have to look at the subcortical and white-matter effects of bilingualism.

4.1. Limitations

To provide measures comparable to those used in the international literature, the LEAP-Q, for which there is a German version for the German native speakers, was chosen. This option was preferred over its alternative, that is, taking a different instrument which would have had to be translated in German first plus potentially necessary validation. The LEAP-Q, however, has a number of other disadvantages, which should be kept in mind. First, it comes in three different versions for participants with only one (monolingual), two (bilingual), or several (multilingual) first languages. Although this is rather practical for individual assessment because (monolingual) participants do not have to complete irrelevant items, it takes some effort to recombine the three versions into one comprehensive database. The next obstacle is how to code the items. For instance, the amount of present exposure to a language is assessed as a subjective judgment with a total of six items rated on a five-point scale each. This design leaves it to the researcher to decide which metric is optimal for the intended analysis (e.g., taking the maximum score given at any of the six items vs. taking an average). Finally, although the LEAP-Q consists of a large set of items, some relevant dimensions that were identified in the recent literature are not, or not sufficiently, covered (e.g., the amount of L2 immersion on top of the present level of L2 proficiency, or in-depth details of the process of L2 acquisition such as place of birth; language spoken in the family in which one grew up; principal language of education; official assessment of language proficiency; language used in partnership(s); language use in the

Table 8
Results for the separate correlation analyses for GMV, CT, and SA in the right IFG done analogously to the analyses for GMV

	Age			Age (cov: Education)			Normalized age (cov: Education. AoA. Profi)		
	Mono	Bi	Fisher's Z	Mono	Bi	Fisher's Z	Mono	Bi	Fisher's Z
Right IFG									
GMV	−0.208	−0.341	1.407	−0.187	−0.337	1.576	−0.187	−0.325	1.444
SA	−0.113	−0.210	0.973	−0.085	−0.206	1.208	−0.085	−0.198	1.127
CT	−0.276	−0.400	1.369	−0.291	−0.397	1.175	−0.291	−0.387	1.060

Significance of Fisher's *Z*: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.
Key: Mono, monolinguals; Bi, bilinguals; CT, cortical thickness; SA, surface area; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; GMV, gray matter volume; MANOVA, multivariate analysis of variance; ROI, region of interest; AoA, age of acquisition.

present and past life circumstances such as work, community area, private activities, etc.—for discussion, cf. Perani et al., 2017—for the relevance of amount of immersion on the brain cf. Pliatsikas et al., 2017). Instead, in the LEAP-Q, the participants are asked to *judge* themselves the impact of the following factors to the acquisition of a language: use with friends, use in family, reading, speech lab/autodidactic learning, TV, and radio. Consequently, although the LEAP-Q had some advantages for the use in a German-speaking cohort from which this sample was drawn, its limitations may stimulate future research adding further relevant details to the actual longitudinal mechanisms by which the higher GMV in bilinguals is acquired. These insights, in turn, might be helpful for society as a whole in supporting and optimizing multilanguage use for quality of life and old-age participation.

5. Conclusion

To conclude, this population-based, large-scale study uncovers the complex relationship between bilingualism and GMV, which is critically modulated by age and which may vary in frontal versus parietal regions of the brain. Bilingualism appears to provide an immediate positive effect on GMV. This GMV difference, however, may diminish with age depending on the individual brain region, with higher persistence in the right than the left inferior frontal cortex. It thus may constitute a structural, focal "brain reserve" for degenerative brain damage.

Disclosure

The authors declare no conflict of interest.

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