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Gray matter volume differences between early bilinguals and monolinguals: A study of children and adults

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Abstract

Gray matter has been shown to be greater in early bilingual adults relative to monolingual adults in regions associated with language (Mechelli et al., 2004), and executive control (EC; Olulade et al., 2016). It is not known, however, if language experience-dependent differences in gray matter volume (GMV) exist in children. Further, any such differences are likely not to be the same as those observed in early bilingual adults, as children have had relatively shorter duration of dual-language exposure and/or less development of brain regions serving EC. We tested these predictions by comparing GMV in Spanish–English early bilingual and English monolingual children, and Spanish–English early bilingual and English monolingual adults ($n = 122$). Comparing only children revealed relatively more GMV in the bilinguals in bilateral frontal, right inferior frontal, and right superior parietal cortices (regions associated with EC). Bilinguals, however, had less GMV in left inferior parietal cortex (region associated with language). An ANOVA including these children with bilingual and monolingual adults revealed interactions of Language Background by Age Group. There were no regions of more GMV in bilinguals relative to monolinguals that were less pronounced in children than adults, despite the children's shorter dual-language experience. There were relative differences between bilingual and monolingual children that were more pronounced than those in adults in left precentral gyrus and right superior parietal lobule (close to, but not directly in areas associated with EC). Together, early bilingual children manifest relative differences in GMV, and, surprisingly, these do not diverge much from those observed in studies of bilingual adults.

KEYWORDS
children, GMV, Spanish–English bilingual, VBM

1 | INTRODUCTION

Bilingualism is common around the world. The study of bilingualism offers a unique opportunity to inform mechanisms underlying experience-dependent neuroplasticity for cognitive functions and the brain systems that serve them. The focus of this study is on bilinguals who acquire their two languages early, by age 6 years, and how they differ in brain anatomy from monolinguals. Adults who are early bilinguals have been shown to have relatively more gray matter in left parietal cortex (Mechelli et al., 2004), a region associated with language processing. Another study found that early bilingual adults had more gray matter volume (GMV) than monolingual adults in left Heschl's gyrus (location of primary auditory cortex) and attributed this to lifelong expertise in language (Ressel et al., 2012). However, differences in GMV in early bilingual adults also exist in brain regions outside of those associated with language, such as right parietal areas (Mechelli et al., 2004; Olulade et al., 2016) and bilateral frontal areas (Olulade et al., 2016) known to subserve executive control (EC). These observations are fitting with the notion that in addition to conferring the benefits of speaking two languages, bilingualism heightens some aspects of EC (Bialystok, 1999; Peal & Lambert, 1962) as a consequence of having to constantly suppress and select between the two languages (Green & Abutalebi, 2013).

These observations in early bilingual adults shed light on the understanding of experience-dependent neuroplasticity, but they also indicate the need to consider early bilinguals separately in GMV studies (in healthy participants and those with disorders), raising concerns about results from studies that do not control for participants' language background. For example, GMV differences associated with the early dual-language experience described above, converge in their anatomical location with those areas associated with disorders of language processing and disorders of EC. Specifically, the language-based reading disability developmental dyslexia is associated with less GMV in areas that subserve language, and ADHD is associated with less GMV in areas that subserve EC (McGrath & Stoodley, 2019). Studies into these disorders hardly ever take into consideration whether their participants have a bilingual background. This is illustrated by the 15 studies included in a meta-analysis of GMV in dyslexia and by the 22 studies included in a meta-analysis of GMV in ADHD, where only one study per meta-analysis reported on the language background of their participants (McGrath & Stoodley, 2019). To address these concerns, it is critical to have a clear understanding of the salient differences in GMV between early bilinguals and monolinguals.

To date, there have only been studies comparing GMV in adults who are early bilinguals or monolinguals, but none in children. The question of whether an early dual-language experience influences GMV is especially important for studies of children and adolescents, as the results have ramifications for understanding the anatomical development of brain regions associated with language processing and brain regions associated with EC, which contribute to children's academic performance and social development (Finucci et al., 1985; Visu-Petra et al., 2011). There are several reasons why one might expect that GMV differences observed in children who are early bilinguals relative to monolinguals may not be the same as those reported in adults. One reason is that children will have had less time to exercise the use of their two languages. Generally, the literature on experience-dependent plasticity reports on differences in GMV that depend on the duration of the experience or training. Based on this literature, due to their longer dual-language experience early bilingual adults would be expected to have more GMV differences (relative to their monolingual peers) than those observed in a similar comparison conducted in children. A prominent example of this phenomenon is the observed relationship between London cab drivers' posterior hippocampal GMV and the number of years driving a cab (Maguire et al., 2000, 2006). Other studies have shown similar effects of duration-dependent differences in GMV for skills such as music, sports, and yoga (Groussard et al., 2014; Hüfner et al., 2011; Villemure et al., 2015, respectively). Based on these studies, we hypothesize that any GMV differences in bilingual relative to monolingual children would be less pronounced relative to the analogous comparison in adults since early bilingual children have used both languages over a shorter extent of time relative to early bilingual adults.

A second reason to expect age-dependent differences in GMV in comparisons of early bilinguals and monolinguals are large-scale changes in brain structure that occur between childhood and adulthood, with significant thinning of gray matter with increasing age (Sowell et al., 2003). At the same time, this cortical thinning is interspersed with regions of gray matter thickening in left hemisphere regions associated with language (Gogtay et al., 2004; Sowell et al., 2004). The reports of greater GMV in bilingual adults therefore only represent experience-dependent changes attributed to bilingualism at a time when most of these extensive developmental changes have reached completion, raising the question of the impact of early bilingualism on GMV in children and adolescents. A specific example of how these developmental changes may interact with the bilingual experience is in EC. Brain regions that serve EC are the last to mature in development, consistent with lower EC skills in children than adults (Bunge et al., 2002; Fiske & Holmboe, 2019; Huizinga et al., 2006). As noted above, some behavioral studies have reported an advantage in bilinguals relative to monolinguals on various EC tasks (for review see Bialystok et al., 2012; Hilchey & Klein, 2011). Importantly for the current study, it has been suggested that the differences in performance on EC tasks observed in bilingual (relative to monolingual) children may be more pronounced than those in bilingual (relative to monolingual) adults (Bialystok et al., 2005). The purported explanation for this pattern is that the underdeveloped EC skills in children make the heightened EC in bilingual children more obvious, while bilingual young adults (typically university students) no longer reap the benefit of the subtle effect of the advantage (Bialystok et al., 2012). Based on the notion that EC for bilinguals is heightened in children, we hypothesized that GMV differences in bilingual children (relative to monolingual children) in regions serving EC may be more pronounced or widely distributed than those in bilingual adults (relative to monolingual adults).

For the first study, we used a *t*-test to address the question of whether there are neuroanatomical differences in Spanish–English early bilingual children compared to monolingual children. For the second study, we used a factorial design to directly test whether the effect of an early bilingual experience on GMV is the same for children and adults. This allows for the comparison of early bilingual and monolingual children relative to the same comparison in adults, thereby providing insights into whether there is an effect of early bilingualism on GMV that is age-dependent in the same study (rather than solely relying on the existing literature of GMV studies in early bilingual adults). Considering that GMV differences are influenced by the amount of experience (Maguire et al., 2006), we hypothesized that any differences in GMV between early bilingual and monolingual children in areas associated with language processing would be less pronounced relative to those observed in their adult counterparts, since early bilingual adults have used their two languages for longer. Another modulating factor could be the developmental reduction of GMV from childhood to adulthood, so that age interacts with anatomical modifications following a dual-language experience. While there are several candidate regions that may show this kind of interaction, we hypothesized that those involved in EC may be the most likely to show this effect due to the underdeveloped EC skills in children relative to adults (Bialystok et al., 2012). Together these two studies will elucidate whether there are anatomical differences associated with early bilingualism in children and if these are affected by age/development.

2 | METHODS

2.1 | Participants

All participants were recruited and tested through methods and materials approved by the Georgetown University Institutional Review Board. Fliers and information were distributed at community events for children and local bilingual schools, as well as around the university and surrounding community in the Washington, DC. Written informed consent was obtained from all participants at the beginning of the study. Only those participants who reported no history of neurological or psychological disorders were included in the study.

All of the bilinguals (children and adults) had to have learned Spanish and English before or by the age of 6 years to be included in the study. This was our criterion for deeming them "early bilinguals." On average, they were exposed to Spanish at age 0.04 years (range 0–2 years of age) and English at age 2.4 years (range 0–6 years of age). One-third of the bilinguals reported simultaneous exposure to the two languages from birth and the remainder (except for one participant) reported learning Spanish before English. All of the bilinguals were cultural bilinguals and as such had learned both languages as a function of their family and/or environment. These cultural early bilinguals (unlike successful second-language learners) afford an opportunity to study the influence of a dual-language experience that is not driven by other factors, such as aptitude for second language learning. On the other hand, all of the monolinguals were native English speakers with little or no experience with another language. A subset of the adults (bilingual and monolingual) were included in a prior GMV study focused on adults (Olulade et al., 2016).

2.1.1 | Bilingual children versus English monolingual children

Participants for the first study included 20 Spanish–English bilingual children (average age 9.8 ± 1.5 years; 13 female and 7 male) and 34 monolingual children (average age 9.2 ± 2.6 years; 19 female and 15 male; see Table 1). A two-sample *t*-test revealed no statistical difference between the groups in age ($t[52] = -0.897$, $p = .374$), and a chi-squared test of association revealed no statistical difference in sex distribution ($\chi^2[1, n = 54] = 0.434$, $p = .510$).

Studies comparing bilinguals to monolinguals can be confounded by socioeconomic status (SES). Using the scoring system described by Noble et al. (2015), [less than 7 years of school = 6; 7–9 years of school = 8; 10–11 years of school = 10.5; high school graduate = 12; some college (1–3 years, Associate's Degree) = 14; 4-year college graduate (Bachelor's Degree) = 16; and professional degree (Post-Bac, Master's Degree, PhD, MD, JD, LLD) = 18] we calculated the education level for the children's parents. Education scores for both parents were averaged, and group data were found not to differ between the parents of the bilingual children (16.8 ± 2.1) and the parents of the monolingual children (16.8 ± 1.5; two-sample *t*-test, $t[52] = -0.0119$, $p = .991$).

Studies on GMV can be confounded by reading ability because GMV is lower in those with lower reading proficiency as has been demonstrated in studies of the reading disability developmental dyslexia (Eckert et al., 2016; Linkersdörfer et al., 2012; McGrath & Stoodley, 2019, for review see Eden et al., 2015). To avoid this potential confound we measured English single real word reading ability with the Woodcock-Johnson Word Identification subtest (Woodcock, 1987; Woodcock et al., 2001). This is a standardized measure that is normed for age, with a standard score of 100 representing the average and scores from 85 to 115 representing the normal range. All children, bilinguals and monolinguals, had a standard score greater than 85, indicating that their reading abilities fell within or above the "normal range." There were no differences in reading proficiency between the bilingual children (113 ± 11.5) and the monolingual children (118 ± 12.0; two-sample *t*-test, $t[52] = 1.47$, $p = .147$).

Taken together, any differences revealed for GMV in the first study comparing bilingual and monolingual children cannot be attributed to age, sex, SES, or English reading proficiency.

As is common in studies of bilingualism, we gauged the bilingual participants' language competence in their two languages (Spanish and English) using the questionnaire by Meschyan and Hernandez (2006). For the children, this questionnaire was given to the parents to complete on behalf of their children using a scale of 1–7 with 1 indicating "low competence" and 7 "native-like competence." The bilingual children's overall proficiency in English (6.7 ± 0.4) and in Spanish (6.0 ± 0.9) was high, with English reported to be stronger than Spanish (paired-samples *t*-test, $t[19] = 3.67$, $p = .002$). Above we report the

TABLE 1 Participant demographics for early bilingual and monolingual children

	Bilingual children	Monolingual children	*t*-test or χ^2 test of association results
n	20	34	–
Age (years)	9.8 ± 1.5	9.2 ± 2.6	n.s.
Sex (F/M)	13/7	19/15	n.s.
SES score	16.8 ± 2.1	16.8 ± 1.5	n.s.
English single real word reading	113 ± 11.5	118 ± 12.0	n.s.

Note: Counts reported for group size and sex (F/M). Average and standard deviation reported for age, SES, and English single real word reading scores. Statistical tests are in the right column. SES score = average education score of children's parents; English single real word reading score = Woodcock-Johnson III Word Identification subtest standard score.

TABLE 2 Participant demographics for early bilingual and monolingual children and adults

	Bilingual children	Monolingual children	Bilingual adults	Monolingual adults	Statistical test for interaction
n	20	34	26	42	–
Age (years)	9.8 ± 1.5	9.2 ± 2.6	22.2 ± 2.8	22.8 ± 3.1	ANOVA n.s.
Sex (F/M)	13/7	19/15	18/8	20/22	χ^2 test of association n.s.
SES	16.8 ± 2.1	16.8 ± 1.5	15.0 ± 2.14	15.3 ± 1.9	n/a
English single real word reading	113 ± 11.5	118 ± 12.0	103 ± 5.7	110 ± 9.5	ANOVA n.s.

Note: Counts reported for group size and sex (F/M). Average and standard deviation reported for age, SES, and English single real word reading scores. Statistical tests are in the right column. SES score = average education score of children's parents and individual education score for adults; English single real word reading score = Woodcock-Johnson III Word Identification subtest standard score.

bilingual children's high average English reading proficiency on the Woodcock-Johnson Word Identification subtest. Using the Spanish version of this standardized test, the Word Identification subtests from the Batería III Woodcock-Muñoz: Pruebas de aprovechamiento (Munoz-Sandoval et al., 2005), we also evaluated their single real word Spanish reading proficiency and found it to be high (124.9 ± 13.4), with all bilingual children having a standard score of 85 or above. These strong reading skills in English and in Spanish on this objective measure indicate high levels of proficiency in both languages (and suggest that the parents may have been underestimating their children's Spanish language abilities). Statistical analyses of all demographics were conducted using Jamovi (https://www.jamovi.org).

2.1.2 | Factorial analysis of bilinguals versus monolingual children and adults

For the second study, in addition to these two groups of children, we included 26 Spanish–English bilingual adults (average age 22.2 ± 2.8 years; 18 female and 8 male) and 42 monolingual adults (average age 22.8 ± 3.1 years; 20 female and 22 male) for a total of 122 participants (see Table 2). To ensure that any results in GMV arising from the interaction of Language Background (bilingual vs. monolingual) and Age Group (children vs. adults) could not be accounted for by other factors, we entered chronological age for all four groups into an ANOVA and found no interaction ($F[1] = 1.5246$, $p = .219$). Likewise, a chi-squared test of association comparing sex distribution over the four groups revealed no interaction (($\chi^2[1, n = 122] = 3.028$, $p = .082$).

We gauged SES using the adult participants' own current level of education. We did not enter education level of the bilingual adults (15.0 ± 2.1) and monolingual adults (15.3 ± 1.9) into an ANOVA with the parents' education of the bilingual and monolingual children (described above) to test for an interaction, because many of the adults were still in the process of completing their education (as such their current education would underestimate their SES). However, we could compare bilingual and monolingual adults, and found these not to differ on SES (two-sample *t*-test, $t[62] = 0.402$, $p = .689$). Overall, SES was matched for the bilingual and monolingual children and separately for the bilingual and monolingual adults.

Just as in the children, all adults (bilingual and monolingual) had a standard score of 85 or above on the English single real word reading test (Woodcock-Johnson Word Identification subtest), indicating that their reading fell within or above the "normal range." These English reading scores for the Spanish–English bilingual adult group (103 ± 5.7) and English-speaking monolingual adult group (110 ± 9.5) were entered into an ANOVA together with those of the children (bilingual group and monolingual group, described above) and there was no interaction between Language Background and

Age Group for English reading proficiency ($F[1] = 0.171$, $p = .680$). As such, the four groups were equated on this standardized English reading proficiency test.

Taken together, our four groups were well matched, and any interaction of Language Background and Age Group for GMV in the second study cannot be attributed to age, sex, SES or English reading proficiency.

Turning to the bilinguals, based on their completion of the questionnaire by Meschyan and Hernandez (2006), the bilingual adults were highly proficient in their overall measure of English (6.6 ± 0.5) and in Spanish (6.4 ± 0.7), with no differences between their two languages (paired-samples *t*-test, $t[25] = -1.65$, $p = .111$). When merging these data with those of the bilingual children (described above) for a repeated-measures ANOVA, there was no interaction ($F[1] = 3.04$, $p = .088$), suggesting that the balance between English and Spanish proficiency was similar in the bilingual children and the bilingual adults. As in the children, we measured Spanish reading proficiency on the Spanish version of the Word Identification subtests from the "Batería III Woodcock-Muñoz: Pruebas de aprovechamiento" (Munoz-Sandoval et al., 2005) and found the bilingual adults' Spanish reading proficiency to be high (117.7 ± 11.0), with all scoring 85 or above. Further, this Spanish reading ability in the bilingual adults was similar to that of the bilingual children (described above), with no statistical difference between the two groups (two-sample *t*-test, $t[44] = 2.0$, $p = .052$). This again demonstrated that the two bilingual groups (children and adults) were well matched and that both had strong proficiency in each of their languages. Statistical analyses of all demographics were conducted using Jamovi (https://www.jamovi.org).

2.2 | MRI data acquisition

Image acquisition was performed using a 3T Siemens Trio scanner located in the Center for Functional and Molecular Imaging at the Georgetown University Medical Center. For each participant, high-resolution T1-weighted MR images were acquired using the following parameters: TR = 1600 ms, TE = 3.37 ms, flip angle = 15°, field-of-view = 256 mm. Voxel size was 1 mm × 1 mm × 1 mm.

2.3 | MRI data analysis

All images were assessed (blind) for quality on a scale of 1 (optimal image) to 5 (severely distorted image) and reoriented to the anterior commissure to reduce inter-subject spatial variability. Overall, 10 subjects were excluded due to anatomical anomalies or poor image quality, resulting in the sample sizes described above. Preprocessing of images was performed in SPM12 using the automated Voxel-Based Morphometry (VBM) technique (Ashburner & Friston, 2000) and methods outlined by Ashburner (2015). The images were co-registered to the white matter tissue probability map and then segmented into gray matter, white matter, and cerebrospinal fluid images. Images were then used to create a study-specific template and spatially normalized to the Montreal Neurological Institute (MNI) stereotaxic space via affine registration of the generated template to the MNI template using DARTEL (Ashburner, 2007). Images were examined to confirm the accuracy of the normalization process and then smoothed with a Gaussian kernel of 10 mm full width at half maximum. Finally, to reduce edge artifacts, the intensity thresholding of the images was set to 0.2.

2.4 | MRI statistical analysis

Statistical analysis of gray matter images was performed using SPM12.

2.4.1 | Bilingual children versus monolingual children

To compare bilingual children with their monolingual peers for the first study, we conducted a two-sample *t*-test (voxel-wise height threshold of $p < .005$, false discovery rate [FDR]; cluster-level extent threshold of $p < .05$). Total intracranial volume (ICV, i.e., combined value of total GMV, white matter volume, and cerebrospinal fluid volume) was included as a covariate of no interest.

2.4.2 | Factorial analysis of bilingual and monolingual children and adults

For the second study, to test whether GMV differences between bilinguals and monolinguals are different in children than in adults, we performed a 2 × 2 full factorial analysis using Language Background (bilingual vs. monolingual) and Age Group (children vs. adults) to test for an interaction (voxel-wise height threshold of $p < .005$, FDR; cluster-level extent threshold of $p < .05$). Total ICV was included as a covariate of no interest.

Following the factorial analysis, we used MarsBaR toolbox (Brett et al., 2002) in SPM12 to create masks of the clusters that showed a significant Language Background by Age Group interaction and then extracted the volume for each of the clusters. These volumes were used to conduct post hoc *t*-tests ($p < .05$) to determine the direction and significance of each cluster emerging from the Language Background × Age Group interaction.

2.4.3 | Anatomical labels

The publicly available label4MRI package (https://github.com/yunshiuan/label4MRI) was used to determine Brodmann's areas and anatomical labels of the coordinates outputted by SPM12. This package uses the Atlas of Brodmann's areas and the Automated Anatomical Labeling Atlas (Tzourio-Mazoyer et al., 2002) respectively.

3 | RESULTS

3.1 | Bilingual children versus monolingual children

As shown in Figure 1 (cerebellum is not depicted in Figure 1) and Table 3, bilingual children exhibited greater GMV in eight clusters compared to monolingual children. Peaks for two of these clusters were located on the *left*, in precentral gyrus (BA 6); and in cerebellum lobule VIII extending to lobule VIIb. Peaks for the other six clusters were located on the *right*, in inferior orbitofrontal gyrus (BA 47); in parahippocampal gyrus (BA 36) extending anteriorly to inferior orbitofrontal gyrus (BA 47); in supplementary motor area (BA 6 and BA 8); in cerebellum lobule VIII; in postcentral gyrus (BA 7) extending posteriorly to superior parietal lobule (BA 7); and in precuneus (BA 30) extending posteriorly to calcarine (BA 18) and inferiorly to fusiform gyrus (BA 36).

The opposite contrast revealed that there were five clusters where the bilingual children had less GMV than the monolingual children. Peaks for four clusters were located on the *left*, in gyrus rectus (BA 11) extending superiorly to medial orbitofrontal gyrus (BA 10); in supramarginal gyrus (BA 40) extending inferiorly to superior temporal gyrus (BA 22); in angular gyrus (BA 39) extending posteriorly to middle occipital gyrus (BA 19 and BA 39); and in superior occipital gyrus (BA 19) extending inferiorly to middle occipital gyrus (BA 19). The *right* cluster was located in cerebellum lobule IX extending to the vermis lobule X.

3.2 | Factorial analysis of bilingual and monolingual children and adults

3.2.1 | Language Background × Age Group interaction

A Language Background by Age Group interaction was seen in seven regions (Figure 2 and Table 4). Our main prediction was for exponential interaction effects, where differences between bilinguals and monolinguals would be either minimized or magnified in children relative to adults. Post hoc *t*-tests conducted on the seven regions emerging from the interactions revealed no regions where the greater amount of GMV found in bilinguals relative to monolinguals was minimized in children relative to adults (due to shorter dual-language experience). Rather, greater GMV in bilingual than monolingual children was magnified relative to adults due to the absence of such a GMV difference between bilingual and monolingual adults in two regions: in *left* precentral gyrus (BA 6); and in *right* superior parietal lobule (BA 1 and BA 7) extending into postcentral gyrus (BA 5). Notably, these findings of a GMV difference in the bilingual children coincided with the expected age-related difference of less GMV in bilingual adults relative to bilingual children, but this age-related effect was absent in the monolinguals.

The other five regions emerging from the interaction analysis had antagonistic patterns of interactions. The *left* middle temporal gyrus (BA 21) showed less GMV in bilingual relative to monolingual children while there was no difference in this region between the two adult groups; and, bilinguals, but not monolinguals, had more GMV in adults relative to children. The other four regions were in the *right* supplementary motor area (BA 6 and BA 8); inferior temporal gyrus (BA 21) extending into middle temporal pole (BA 38); fusiform gyrus (BA 36); and cerebellum Crus II extending into Lobule VIIb and contralateral Cruz II. These regions all had more GMV in bilingual relative to monolingual children, while it was the reverse in adults (bilingual < monolingual). Further, in *right* supplementary motor area bilinguals, but not monolinguals, had less GMV in adults relative to children, while in right inferior temporal gyrus and right cerebellum monolinguals, but not bilinguals, had more GMV in adults relative to children. *Right* fusiform gyrus was the only region to show a complete antagonistic interaction, where bilinguals had more GMV than monolinguals in children, with the reverse in adults; and at the same time, bilinguals had more GMV in children relative to adults, while monolinguals had less GMV in children relative to adults. To provide some context for these findings, we consider the main effect of Language Background and the main effect of Age Group next.

3.2.2 | Main effect of Language Background

The main effect of Language Background (Figure 3 and Table 5) revealed five clusters where bilinguals had greater GMV than

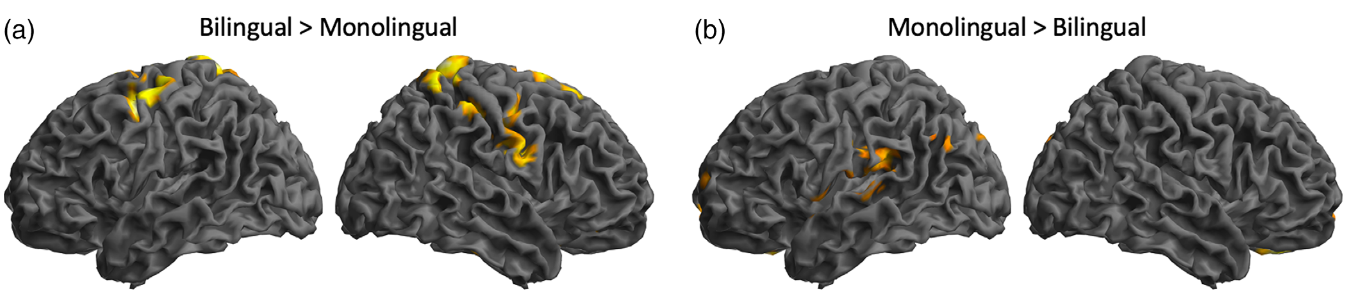

FIGURE 1 Gray matter volume differences between Spanish–English early bilingual children and English-speaking monolingual children. (a) Clusters with more GMV in bilingual than in monolingual children. (b) Clusters with more GMV in monolingual than in bilingual children. Voxel-wise height threshold $p < .005$. FDR cluster-level extent threshold $p < .05$. Clusters in the cerebellum not included in figure. Coordinates for significant clusters are in Table 3.

TABLE 3 MNI coordinates for maxima of GMV differences between early bilingual and monolingual children

MNI coordinates						
X	*Y*	*Z*	Anatomical region	BA	*Z*	k_E
Bilingual > monolingual						
−33	**−12**	**70**	**Left precentral gyrus**	**6**	**4.35**	**2419**
−38	*−3*	*64*	*Left precentral gyrus*	*6*	*4.26*	
−36	*−20*	*70*	*Left precentral gyrus*	*6*	*4.15*	
−44	**−40**	**−51**	**Left cerebellum lobule VIII**		**3.32**	**1618**
−40	*−56*	*−52*	*Left cerebellum lobule VIII*		*3.18*	
−50	*−46*	*−51*	*Left cerebellum lobule VIIB*		*3.15*	
24	**36**	**−8**	**Right inferior orbitofrontal gyrus**	**47**	**4.46**	**424**
32	*36*	*−4*	*Right inferior orbitofrontal gyrus*	*47*	*3.51*	
15	**2**	**−33**	**Right parahippocampal gyrus**	**36**	**3.7**	**1758**
15	*−6*	*−38*	*Right parahippocampal gyrus*	*36*	*3.69*	
15	*14*	*−28*	*Right inferior orbitofrontal gyrus*	*47*	*3.64*	
8	**−4**	**74**	**Right supplementary motor area**	**6, 8**	**4.1**	**1629**
6	*6*	*68*	*Right supplementary motor area*	*6*	*3.72*	
9	*22*	*52*	*Right supplementary motor area*	*8*	*3.58*	
24	**−39**	**−57**	**Right cerebellum lobule VIII**		**4.02**	**443**
28	*−36*	*−51*	*Right cerebellum lobule VIII*		*3.52*	
34	*−39*	*−56*	*Right cerebellum lobule VIII*		*3.47*	
20	**−42**	**76**	**Right postcentral gyrus**	**7**	**5.2**	**4799**
36	*−45*	*69*	*Right postcentral gyrus*	*1*	*4.81*	
32	*−56*	*69*	*Right superior parietal lobule*	*7*	*4.53*	
27	**−44**	**6**	**Right precuneus**	**30**	**4.58**	**481**
32	*−51*	*2*	*Right calcarine fissure*	*18*	*4.2*	
21	*−32*	*−16*	*Right fusiform gyrus*	*36*	*3.18*	
Monolingual > Bilingual						
2	**38**	**−30**	**Left gyrus rectus**	**11**	**4.73**	**4615**
9	*52*	*−8*	*Right medial orbitofrontal gyrus*	*10*	*4.14*	
9	*34*	*−30*	*Right gyrus rectus*	*11*	*3.86*	
−45	**−36**	**30**	**Left supramarginal gyrus**	**40**	**4.08**	**3083**
−45	*−2*	*−10*	*Left superior temporal gyrus*	*22*	*3.93*	
−51	*−36*	*16*	*Left superior temporal gyrus*	*22*	*3.56*	
−52	**−72**	**34**	**Left angular gyrus**	**39**	**3.88**	**453**
−52	*−78*	*21*	*Left middle occipital gyrus*	*19*	*3.75*	
−48	*−75*	*40*	*Left middle occipital gyrus*	*39*	*3.58*	
−20	**−92**	**36**	**Left superior occipital gyrus**	**19**	**4.4**	**581**
−34	*−93*	*24*	*Left middle occipital gyrus*	*19*	*4.39*	
−30	*−90*	*34*	*Left middle occipital gyrus*	*19*	*4.31*	
4	**−42**	**−48**	**Right cerebellum lobule IX**		**4.91**	**998**
0	*−44*	*−56*	*Left cerebellum lobule IX*		*3.75*	
2	*−44*	*−39*	*Vermis X*		*3.58*	

Note: Bold indicates anatomical location of peak coordinates of cluster. Italic indicates anatomical location of sub-peaks within clusters.

monolinguals (children and adults combined). Peaks for two of the clusters were on the *left*: supplementary motor area (BA 6) extending rostrally to the superior frontal gyrus (BA 6); and precentral gyrus (BA 6 and BA 4). The remaining three clusters had peaks on the *right*: inferior orbitofrontal gyrus (BA 47 and BA 11); postcentral gyrus (BA 4) extending inferiorly to the supramarginal gyrus (BA 40) and rostrally to the precentral gyrus (BA 6); and paracentral lobule (BA 1) extending to the postcentral gyrus (BA 5 and BA 1).

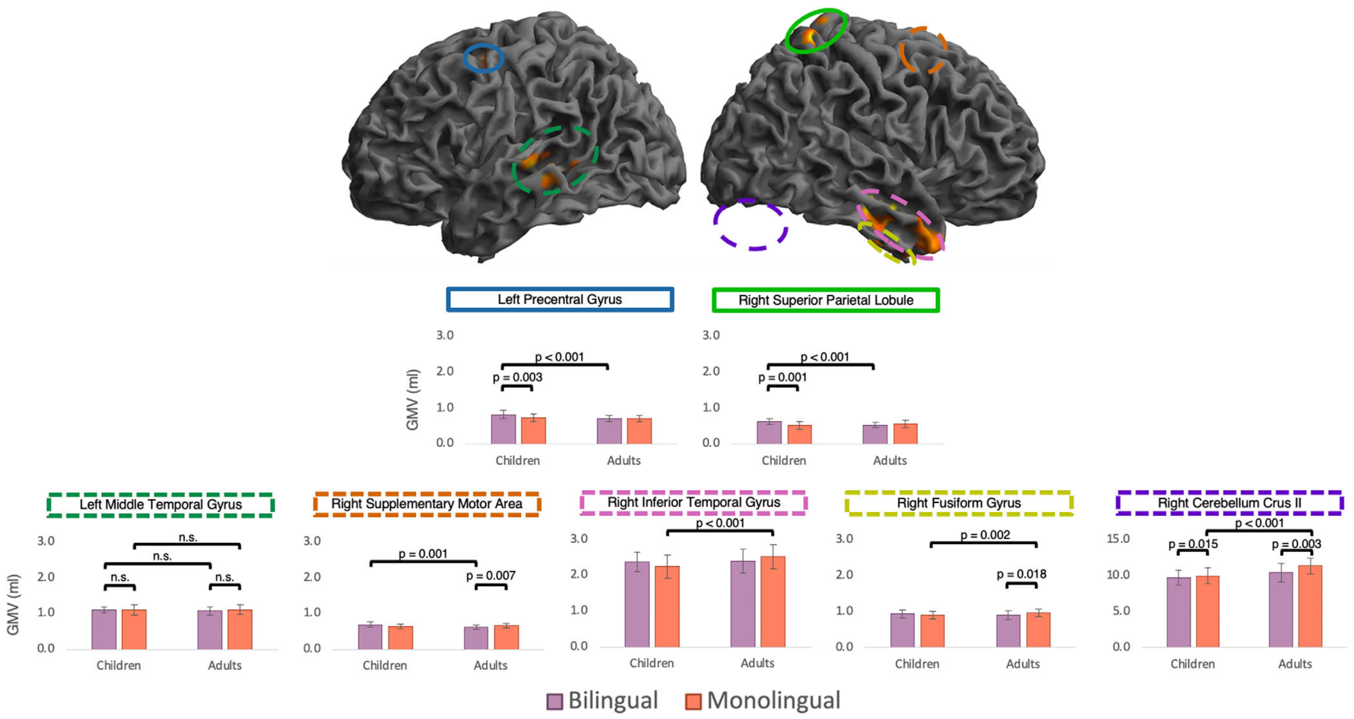

FIGURE 2 Language Background × Age Group interaction. Lateral surface views of anatomical location of clusters emerging from the interaction analysis. Top row shows regions with exponential interaction patterns (solid circles with color-corresponding boxes). Greater GMV in bilingual versus monolingual children was not found to be minimized by relatively greater comparable findings in adults; rather they were more pronounced due to absence of such findings in adults. Bottom row shows regions with antagonistic interaction patterns (dashed circles/boxes). Clusters in the cerebellum not included in figure; right supplementary motor area and right fusiform gyrus clusters not visible due to their respective medial and ventral locations. Whole-brain analysis, with voxel-wise height threshold $p < .005$. FDR cluster-level extent threshold $p < .05$. p-Values reported from post hoc t-tests. Error bars indicate standard deviation. Anatomical coordinates provided in Table 4.

The opposite contrast showed seven regions where monolinguals had greater GMV than bilinguals. Peaks of two clusters were on *the left*: superior temporal gyrus (BA 22) extending medially to the hippocampus (BA 54); and another more anterior cluster in the superior temporal gyrus (BA 22), extending to the supramarginal gyrus (BA 39 and BA 40). The remaining five clusters had peaks on the *right*: inferior orbitofrontal gyrus (BA 47) extending caudally to the inferior frontal gyrus *pars triangularis* (BA 45) and the insula (BA 45); gyrus rectus (BA 11) extending across the midline to left gyrus rectus (BA 11); superior temporal gyrus (BA 22) extending medially to hippocampus (BA 22); cerebellum Lobule IX extending across the midline to left cerebellum Lobule IX; and superior occipital gyrus (BA 19) extending medially to the cuneus (BA 19) and across the midline to left cuneus (BA 19).

3.2.3 | Main effect of Age Group

The main effect of Age Group (Figure 4 and Table 6) revealed an extensive cluster where children had greater GMV than adults (bilinguals and monolinguals combined). The peak of this cluster was in the *right* middle cingulum (BA 31) and extended to the precuneus (BA 31). This cluster, however, encompassed all four lobes and both hemispheres.

In the reverse contrast, three clusters showed greater GMV in the adults relative to the children. One cluster had its peak in the *left* postcentral gyrus (BA 6 and BA 4) extending inferiorly to middle temporal gyrus (BA 21). The other two clusters had peaks in the *right*: postcentral gyrus (BA 4) extending rostrally to the precentral gyrus (BA 6) and inferiorly to the superior temporal gyrus (BA 1); and the other in cerebellum Lobule VIII.

4 | DISCUSSION

Prior studies in adults have shown more GMV in early bilinguals relative to monolinguals and these differences have been attributed to their lifelong dual-language experience. Some of these regions are thought to be involved in language (Mechelli et al., 2004; Ressel et al., 2012), and others in EC (Olulade et al., 2016), dove-tailing with the notion that an early dual-language experience brings about changes in language performance as well as changes in EC. However, no such studies exist for children even though the brain structures reported to be influenced by an early dual-language experience are key players in language, academic, and social development. Further, early bilinguals' unique characteristics of brain anatomy may need to be taken into consideration when recruiting participants, given that they are likely to affect the results of GMV studies. Here, we measured GMV in

TABLE 4 MNI coordinates for maxima of GMV difference emerging from an interaction of Language Background × Age Grouzp

Language Background × Age Group interaction						
MNI coordinates						
X	Y	Z	Anatomical region	BA	Z	k_E
Bilingual > monolingual GMV in adults more pronounced than those in children						
No significant clusters						
Bilingual > monolingual GMV in children more pronounced than those in adults						
−30	**−6**	**57**	**Left precentral gyrus**	**6**	**3.21**	**468**
−36	*−4*	*66*	*Left precentral gyrus*	*6*	*2.89*	
39	**−46**	**64**	**Right superior parietal lobule**	**1**	**3.75**	**544**
30	*−51*	*70*	*Right superior parietal lobule*	*7*	*3.46*	
22	*−42*	*75*	*Right postcentral gyrus*	*5*	*3.31*	
Antagonistic interactions						
−66	**−28**	**2**	**Left middle temporal gyrus**	**21**	**3.59**	**771**
−66	*−44*	*6*	*Left middle temporal gyrus*	*21*	*3.49*	
−58	*−38*	*−6*	*Left middle temporal gyrus*	*21*	*2.98*	
8	**10**	**51**	**Right supplementary motor area**	**6**	**3.19**	**448**
9	*20*	*51*	*Right supplementary motor area*	*8*	*2.87*	
36	**−18**	**−42**	**Right fusiform gyrus**	**36**	**3.84**	**566**
33	*−14*	*−32*	*Right fusiform gyrus*	*36*	*3.74*	
28	*−15*	*−44*	*Right fusiform gyrus*	*36*	*3.44*	
46	**−6**	**−26**	**Right inferior temporal gyrus**	**21**	**4.34**	**1820**
51	*−21*	*−18*	*Right inferior temporal gyrus*	*21*	*4.06*	
56	*10*	*−34*	*Right middle temporal pole*	*38*	*3.97*	
20	**−92**	**−36**	**Right cerebellum (Crus II)**	**n/a**	**4.53**	**5978**
−18	*−82*	*−42*	*Left cerebellum (Crus II)*	*n/a*	*4.15*	
0	*−81*	*−44*	*Right cerebellum lobule VIIb*	*n/a*	*4.1*	

Note: Bold indicates anatomical location of peak coordinates of cluster. Italic indicates anatomical location of sub-peaks within clusters.

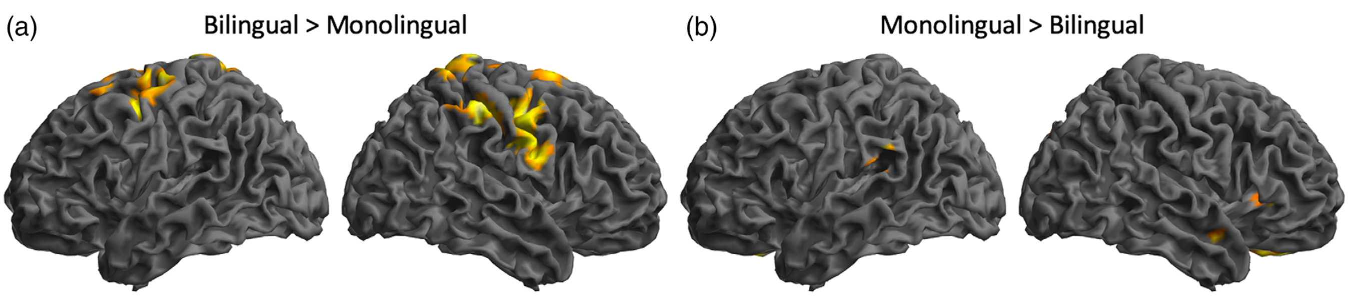

FIGURE 3 Gray matter volume differences between Spanish–English early bilinguals and English-speaking monolinguals (children and adults combined). (a) Clusters with more GMV in bilinguals than in monolinguals. (b) Clusters with more GMV in monolinguals than in bilinguals. Voxel-wise height threshold $p < .005$. FDR cluster-level extent threshold $p < .05$. Clusters in the cerebellum not included in figure. Coordinates for significant clusters are in Table 5.

Spanish–English early bilingual and English-speaking monolingual children to determine if there are between-group differences that already manifest in childhood. The results demonstrated greater GMV in bilingual compared to monolingual children in left and right frontal, right inferior frontal, and right parietal cortices, the latter two being known to be associated with EC. Surprisingly, the results also revealed less GMV in bilingual children (relative to their monolingual peers) in several left-hemisphere regions, including inferior parietal cortex known to be involved in spoken and written language. Expanding the work on anatomical studies of early bilingualism in adult participants to children is important because they reveal the impact of an early dual-language experience on the brain at an earlier stage of the lifespan.

TABLE 5 MNI coordinates for maxima of GMV differences between bilingual and monolingual (children and adults combined)

MNI coordinates						
X	Y	Z	Anatomical region	BA	Z	k_E
Bilingual > monolingual						
−8	**15**	**70**	**Left supplementary motor area**	**6**	**3.64**	**422**
−20	*24*	*64*	*Left superior frontal gyrus*	*6*	*3.51*	
−18	*16*	*69*	*Left superior frontal gyrus*	*6*	*3.3*	
−32	**−10**	**66**	**Left precentral gyrus**	**6**	**4.45**	**2228**
−28	*−24*	*74*	*Left precentral gyrus*	*4*	*3.98*	
−32	*0*	*48*	*Left precentral gyrus*	*6*	*3.93*	
24	**36**	**−8**	**Right inferior orbitofrontal gyrus**	**47**	**4.96**	**378**
28	*36*	*−18*	*Right inferior orbitofrontal gyrus*	*11*	*3.03*	
32	*32*	*−26*	*Right inferior orbitofrontal gyrus*	*47*	*2.8*	
44	**−16**	**33**	**Right postcentral gyrus**	**4**	**4.59**	**6148**
48	*−33*	*46*	*Right supramarginal gyrus*	*40*	*4.46*	
34	*−10*	*44*	*Right precentral gyrus*	*6*	*4.45*	
6	**−40**	**75**	**Right paracentral lobule**	**1**	**4.44**	**2219**
24	*−44*	*75*	*Right postcentral gyrus*	*5*	*4.36*	
16	*−34*	*78*	*Right postcentral gyrus*	*1*	*4.13*	
Monolingual > Bilingual						
−44	**0**	**−14**	**Left superior temporal gyrus**	**22**	**3.37**	**345**
−39	*−14*	*−15*	*Left hippocampus*	*54*	*2.85*	
−64	**−40**	**18**	**Left superior temporal gyrus**	**22**	**4.22**	**427**
−63	*−42*	*27*	*Left supramarginal gyrus*	*39*	*3.71*	
−63	*−36*	*36*	*Left supramarginal gyrus*	*40*	*3.5*	
30	**32**	**−2**	**Right inferior orbitofrontal gyrus**	**47**	**3.53**	**470**
38	*33*	*3*	*Right Inferior Frontal Gyrus pars triangularis*	*45*	*3.5*	
33	*30*	*9*	*Right insula*	*45*	*3.04*	
3	**30**	**−30**	**Right gyrus rectus**	**11**	**4.81**	**3601**
−2	*40*	*−28*	*Left gyrus rectus*	*11*	*3.79*	
8	*38*	*−30*	*Right gyrus rectus*	*11*	*3.79*	
45	**0**	**−15**	**Right superior temporal gyrus**	**22**	**3.68**	**757**
42	*−8*	*−18*	*Right hippocampus*	*22*	*3.3*	
3	**−44**	**−39**	**Right cerebellum lobule IX**		**5.62**	**2546**
10	*−50*	*−34*	*Right cerebellum lobule IX*		*5.41*	
−14	*−48*	*−42*	*Left cerebellum lobule IX*		*4.63*	
26	**−88**	**38**	**Right superior occipital gyrus**	**19**	**4.41**	**338**
4	*−90*	*32*	*Right cuneus*	*19*	*4.06*	
0	*−86*	*38*	*Left cuneus*	*19*	*3.59*	

Note: Bold indicates anatomical location of peak coordinates of cluster. Italic indicates anatomical location of sub-peaks within clusters.

To understand these results in the context of those found in early bilingual versus monolingual adults, and to directly test whether the neuroanatomical impact of early bilingualism is dependent on the age of participants (if it is minimized or magnified by age), we compared the early bilingual and monolingual groups of children with early bilingual and monolingual adults using a factorial analysis. Based on prior studies on experience-induced changes in GMV, we hypothesized that the use of two languages over a shorter time span, such as that experienced by bilingual children (relative to the longer one experienced by bilingual adults), could lead to a relatively smaller GMV difference in bilingual children than adults in areas involved in language (when each group is contrasted to their monolingual peers). At the same time, gray matter in children and adults differs significantly as a function of maturation, raising the question of how this developmental change may interact with any further modifications brought about by a dual-language experience. Specifically, it has also been argued

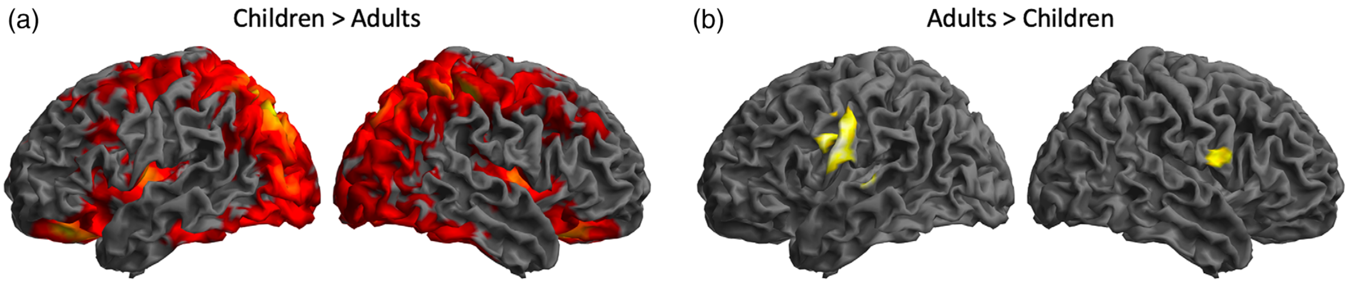

FIGURE 4 Gray matter volume differences between children and adults (bilinguals and monolinguals combined). (a) Clusters with more GMV in children than in adults. (b) Clusters with more GMV in adults than in children. Voxel-wise height threshold $p < .005$. FDR cluster-level extent threshold $p < .05$. Clusters in the cerebellum not included in figure. Coordinates for significant clusters are in Table 6.

TABLE 6 MNI coordinates for maxima of GMV differences between children and adults (bilinguals and monolinguals combined)

MNI coordinates						
X	Y	Z	Anatomical region	BA	Z	k_E
Children > adults						
2	**−30**	**46**	**Right middle cingulum**	**31**	**Inf**	**249,324**
6	*−39*	*50*	*Right middle cingulum*	*31*	*Inf*	
6	*−44*	*57*	*Right precuneus*	*31*	*Inf*	
Adults > children						
−63	**2**	**18**	**Left postcentral gyrus**	**6**	**4.95**	**1800**
−62	*−4*	*34*	*Left postcentral gyrus*	*4*	*4.57*	
−68	*−27*	*4*	*Left middle temporal gyrus*	*21*	*4.5*	
66	**2**	**15**	**Right postcentral gyrus**	**4**	**3.68**	**299**
64	*4*	*24*	*Right precentral gyrus*	*6*	*2.89*	
66	*−6*	*8*	*Right superior temporal gyrus*	*1*	*2.69*	
26	**−64**	**−42**	**Right cerebellum lobule VIII**		**4.7**	**741**
18	*−63*	*−39*	*Right cerebellum lobule VIII*		*3.4*	

Note: Bold indicates anatomical location of peak coordinates of cluster. Italic indicates anatomical location of sub-peaks within clusters.

that adaptations around EC function attributed to bilingualism affect children more than adults, leading us to hypothesize that we may find relatively larger GMV differences between bilinguals and monolinguals in children relative to adults in areas involved in EC. Of the eight brain regions that emerged as an interaction between Language Background (bilingual vs. monolingual) and Age Group (children vs. adults), none followed a pattern that indicated GMV differences in bilingual (relative to monolingual) adults that were more pronounced than those found for bilingual (relative to monolingual) children. However, two regions, left precentral gyrus and right superior parietal lobule, demonstrated more GMV in bilingual relative to monolingual children, heightened in relation to the analogous comparison between bilingual and monolingual adults. The left middle temporal gyrus showed an antagonistic pattern of less GMV in bilingual relative to monolingual children and less GMV in bilingual children relative to bilingual adults. The four remaining interactions also had antagonistic relationships, this time on the right side, with more GMV in bilingual than monolingual children, with the reverse in adults. These findings will be addressed in more detail below in the context of the findings from the main effects of Language Background and the main effects of Age Group.

4.1 | Bilingual children have greater GMV than monolingual children, including some regions associated with executive control

Prior studies in early bilingual relative to monolingual adults found GMV differences in regions known to be involved in EC (Olulade et al., 2016). The current study also found more GMV in early bilingual compared to monolingual children in brain regions associated with EC function. Specifically, we found more GMV in bilingual compared to monolingual children in right inferior orbitofrontal gyrus (BA 47), right supplementary motor area (BA 6/8), right postcentral gyrus (BA 7) extending to the superior parietal lobule (BA 7), and the right precuneus (BA 30). To put this into context, we consider a study of several task-specific meta-analyses of neuroimaging studies of EC, on Stroop Tasks, Spatial Interference Tasks, Stop-Signal Tasks, or Go/No-Go

Tasks and a large meta-analysis across all of these tasks (Cieslik et al., 2015). None of the task-specific meta-analyses (nor the overall meta-analysis) had findings overlapping with our region in right inferior orbitofrontal gyrus (the closest finding being in the Stroop Tasks meta-analysis, less than 10 mm away from ours). Turning to our right supplementary motor cortex finding, the task-specific meta-analyses results for Stroop Tasks, Spatial Interference Tasks, and Stop-Signal Tasks all had foci within our cluster. Finally, while Cieslik et al. (2015) reported right postcentral gyrus and right superior parietal lobule for their Spatial Interference, Go/No-Go, and the overall meta-analyses, their foci were not within our cluster. The other clusters we found to have greater GMV in the bilingual relative to monolingual children, do not appear to be involved in EC. Rather, left precentral gyrus, left and right lobule VIII of the cerebellum are associated with motor movement, while right parahippocampal gyrus and precuneus are associated with memory. As such their role in early bilingualism is not clear. In sum, of the many regions reported to have more GMV in bilingual relative to monolingual children, right supplementary motor cortex and possibly right postcentral gyrus and superior parietal lobule could be indicative of bilingual children exercising relatively greater EC than monolingual children.

When children and adults were combined for the main effects analysis of Language Background, many of the same findings were upheld, with bilinguals again having more GMV than monolinguals in the right inferior orbitofrontal gyrus, and right postcentral gyrus extending into inferior parietal cortex, but notably not right supplementary motor cortex. As in the first study of only children, the right inferior orbitofrontal and postcentral gyri clusters from the main effects analysis (children and adults combined) do not directly overlap with regions reported in the meta-analyses by Cieslik et al. (2015).

4.2 | Bilingual children have less GMV than monolingual children, including brain regions associated with language

Based on earlier studies in adults one might have expected more GMV in early bilingual relative to monolingual children in regions known to be involved in language. Specifically, Mechelli and colleagues found left inferior parietal cortex (angular gyrus, BA 39) to have more gray matter in adult bilinguals than monolinguals, and even more so if the bilinguals were early, rather than late, bilinguals (Mechelli et al., 2004). Surprisingly, we found the opposite: bilingual children had less GMV than monolingual children in several left hemisphere regions, including inferior parietal cortex (supramarginal and angular gyri), which have a prominent role in language and reading (Price, 2012).

The question arises whether these differences reflect the bilingual experience per se or if they can be attributed to other variables that differed between the bilingual and monolingual groups. It is known that brain anatomy in left perisylvian cortex differs between males and females (Goldstein, 2001) and is influenced by age (Gogtay et al., 2004), but the bilingual and monolingual children were matched on both sex and age. These perisylvian regions have also been shown to have less GMV in those with the reading disability developmental dyslexia (Linkersdörfer et al., 2012), but none of the children in either group had poor reading ability and the two groups were matched on reading ability. Similarly, the results cannot be attributed to SES, which has also been shown to be related to brain anatomy in perisylvian regions (Noble et al., 2015), as SES was also equated in the two groups.

Given this, what is the explanation for why early bilingual children have less GMV in the left supramarginal (extending into superior temporal) and angular gyri? fMRI studies have shown that early bilinguals tend to show activity in the same perisylvian cortical regions for their two languages, whereas late bilinguals show less of this kind of overlap between their two languages (Połczyńska & Bookheimer, 2021). It is likely that the language cortex that houses two languages, as in bilinguals, is different in volume than that which houses only one language, as in monolinguals, but the prediction would be for GMV to be greater if subserving two languages, which does not fit with our results. Related to this, bilinguals may have a smaller vocabulary in each of their languages (Bialystok et al., 2010), while their combined vocabulary is greater than that of monolinguals (Allman, 2005); and vocabulary size is positively correlated with gray matter in the left supramarginal gyrus of monolinguals (Lee et al., 2007). Together this would suggest greater GMV in bilinguals, which again is the opposite of what we found. Another area where behavioral studies have identified differences between bilinguals and monolinguals is phonological awareness, with some showing relatively better phonological awareness in bilinguals (Chen et al., 2004; Kovelman et al., 2008; Kuo & Anderson, 2010; Laurent & Martinot, 2010; Marinova-Todd et al., 2010), but others not (Bialystok et al., 2003; Jackson et al., 1998; Martin, 2011). Even if bilinguals do have better phonological awareness, the expectation does not fit our results as better phonological awareness is associated with greater and not less GMV in left supramarginal and angular gyri (He et al., 2013). Lastly, our results may not conform with those of Mechelli et al. (2004) because their study was not on children. However, our observation does not appear to be specific to children, as the comparison of bilinguals versus monolinguals when children and adults were combined (main effect of Language Experience) also revealed less GMV in bilinguals in left superior temporal gyrus extending to supramarginal gyrus. Future studies will need to examine differences between early bilinguals and monolinguals in activation during specific language tasks to shed further light on our findings. The remainder of the regions where GMV was less in bilinguals were left gyrus rectus, left superior occipital gyrus, and right cerebellum lobule IX, regions that do not involve language or EC.

Taken together, bilingual children were found to have differences in GMV compared to monolingual children, generally with more GMV in right hemisphere areas (including an area associated with EC) and less GMV in left hemisphere areas (including an area associated with language). These results were similar to those revealed in the main effect analysis of Language Background in the second study, indicating that the results from children are very similar to those when children and adults are combined. Despite this indication of convergence across both age groups, we also asked if GMV differs in bilinguals and monolinguals depending on their age.

4.3 | Some GMV differences between early bilinguals and monolinguals depend on age

GMV is known to change significantly from childhood to adulthood (Gogtay et al., 2004; Sowell et al., 2003). The main effects analysis for Age Group revealed less GMV in adults relative to children in broad swaths of cortex, most notably in occipital and parietal but also extending to frontal and temporal lobes in both hemispheres. It also identified islands of more GMV in adults relative to children in bilateral postcentral gyri and superior temporal lobe structures. These findings of a general developmental thinning of GMV with some sparing around the perisylvian cortex align with the well-established developmental trajectory of GMV (Gogtay et al., 2004; Sowell et al., 2003). Our central research question was, however, if Language Background and Age interact in how they influence GMV.

The interaction analysis revealed no regions where GMV differences in bilingual (vs. monolingual) children were less pronounced than those found in bilingual (vs. monolingual) adults, a relationship we had predicted based on the adults' relatively longer dual-language experience. The expectation that there would be relatively greater GMV differences in bilingual adults than in bilingual children follows from reports of a relationship between GMV in the hippocampus and the number of years working as a taxicab driver (Maguire et al., 2000); or between GMV in the frontal and temporal lobes and the number of years practicing yoga (Villemure et al., 2015). Not finding an effect that can be attributed to longer dual-language experience in adults could be due to the fact that their dual-language experience began in early childhood and was not a training experience undertaken during adulthood (such as the London taxicab drivers; Maguire et al., 2000). An example of participants who underwent an extensive training for second-language learning as adults is provided by Mårtensson et al. (2012), who found increases in cortical thickness in left frontal and temporal lobes after 3 months of intensive second-language learning relative to those who did not learn a second language. However, our participants began their dual-language experience early and as a function of family/social circumstances rather than by choice. Not only did the participants in Mårtensson et al. (2012) learn a second language later in life, but their second language learning may well have been driven by an aptitude that attracted them to and facilitated their acquisition of a second language. Together, our results suggest that for a skill that is acquired early, the pattern that more experience is related to more GMV does not apply; rather, growth in GMV brought about by early bilingualism has already occurred by the time children are around 9 years of age.

On the other hand, there were two regions that showed greater GMV in bilingual compared to monolingual children where at the same time there were no differences between bilingual and monolingual adults: left precentral gyrus (BA 6), and right superior parietal lobule (BA 1 and BA 7) expanding into right precentral gyrus (BA 5). It has been suggested (Bialystok et al., 2012) that heightened EC performance in bilinguals may be observed at those life stages when EC is not at peak capacity (childhood and adults above 60), and that it does not manifest as reliably in young adulthood when EC is at peak capacity (Bialystok et al., 2005). Based on these findings, one may expect relatively more GMV in areas of EC function in bilinguals that are significantly more pronounced in children relative to adults due to heightened EC performance in bilingual children; or a finding of relatively less GMV in areas of EC function in bilinguals that are significantly more pronounced in children relative to adults due to advanced maturation (i.e., thinning of the cortical mantle) in the bilingual children. The latter was not observed, but the former was supported by an interaction effect in left precentral gyrus and right superior parietal lobule/precentral gyrus, two areas identified in the first study comparing bilingual and monolingual children. However, the interaction seems to be driven by an absence of the expected age-specific GMV difference between monolingual children and adults (Figure 2) which is pervasive in those regions (see main effects of Age Group). As such, this result is not so much a reflection of a differential effect of bilingualism, but rather due to a small region of cortex in the monolingual adults having escaped the developmental cortical thinning process. Further, as already noted above, a closer look at the location of these two regions (from Study 1) does not place them squarely in areas associated with EC when considered in the context of the meta-analyses by Cieslik et al. (2015). The functional properties of the left precentral gyrus are numerous, making it difficult to attribute it to just EC. While it has been implicated in speech production (Behroozmand et al., 2015), the coordinates of those studies are more rostral and inferior within the left precentral gyrus. Turning to the right superior parietal lobule, its maxima was in BA 1 of primary somatosensory cortex and extended into BA 7 and BA 5, the latter also being known to play a role in movement and visuomotor coordination.

In the left hemisphere, the middle temporal gyrus (BA 21) showed relatively less GMV in the bilingual children with no difference between the bilingual and monolingual adults. This observation is of interest given the somewhat surprising finding in the first study of bilingual children having less GMV in left perisylvian language areas, namely supramarginal gyrus extending into the left superior temporal gyrus (BA 22). Since this is the first study of children and there have been no reports of less GMV in bilinguals relative to monolinguals in left perisylvian cortex in the prior studies limited to adults, this observation at first seems to be age-specific. However, the main effects analyses shed further light on the specific pattern in this general region. The lower GMV in superior temporal gyrus (BA 22) found in the bilinguals in the study of only children, was also found in the bilinguals when combining children and adults. Returning to the left middle temporal gyrus (BA 21) which is situated in cortex that follows an overall different developmental pattern compared to the rest of the brain, with GMV being greater in adults than children, the interaction occurred because the bilinguals showed such a difference in GMV between children and adults (children < adults) with no age-depended difference in the monolinguals here despite it being prevalent in neighboring regions (main effects of Age Group results show left middle temporal gyrus (BA 21) has more GMV in adults than children). This subregion identified in the interaction therefore again represents a pocket of cortex that was spared the general change in that region, in this case, an apparent increase of GMV from childhood to adulthood.

While our focus of the interaction was on exponential outcomes, the right hemisphere supplementary motor area (BA 6 and BA 8), fusiform gyrus (BA 36), inferior temporal gyrus (BA 21 and BA 28), and cerebellum Crus II all had antagonistic interactions, with relatively more GMV in the bilingual children and relatively less GMV in the bilingual adults. In addition to this relationship, the right supplementary motor area also revealed the expected greater GMV in bilingual children than bilingual adults, but there were no differences between monolingual children and monolingual adults, again showing an apparent sparing of the typical-observed developmental effects (loss of GMV with increasing age) in this region. In the inferior temporal gyrus, fusiform gyrus, and cerebellum Crus II there was less GMV in monolingual children than in monolingual adults, indicating a complete reversal of the normal developmental pattern in the monolinguals in these regions, even though they are located generally in areas that showed less GMV in adults than children. Only the right fusiform gyrus revealed significant differences between both the language background and the age of the groups. Here, bilingual children had more GMV than monolingual children, with the reverse in adults, while bilinguals had more GMV in children than adults with the reverse in monolinguals. While this pattern is perhaps one of the more striking observations, indicating differences between bilinguals and monolinguals at both ages, but in opposite directions, it is not clear why the bilingual experience and age would have such an interaction effect in the right fusiform gyrus.

4.4 | The importance of studying early bilingual children and adults

Gray matter volume differences in early bilinguals have not yet been studied in children and to date, there are only three studies comparing GMV in early bilingual and monolingual adults. There are more GMV studies in bilinguals generally, but here we focus on early bilinguals, as these afford an opportunity to study the influence of a dual-language experience that is not driven by other factors. While a recent meta-analysis of GMV studies questioned the existence of GMV differences in bilinguals (Danylkiv & Krafnick, 2020), the studies entered into the meta-analysis were mostly on late bilinguals. As pointed out by García-Pentón et al. (2016), heterogeneity in criteria for determining bilingualism (including age of language acquisition) as well as methodological differences amongst studies, have led to inconsistent findings in studies of anatomical discrepancies between bilinguals and monolinguals. The current study therefore specifically focused on early bilinguals and is the first to study GMV in early bilingual children. However, this also means that we studied a limited section of the bilingual population, which, as a whole, is highly heterogeneous; and we do not expect our results to generalize to this population.

Specifically, we selected our bilinguals to be cultural early bilinguals and not successful second-language learners from a monolingual environment. This was to avoid participants with an unusual aptitude for second-language learning. Nevertheless, there will generally still be some variability amongst cultural early bilinguals in aptitude for language learning. However, in our group of early bilinguals, the range of language-learning aptitude is likely to be narrow since we included only those participants with good proficiency in their two languages (e.g., reading in the normal or above normal range on a standardized test in both languages). Likewise, for the monolingual participants, we also only included those participants with good proficiency in English (e.g., based on reading in the normal or above normal range). Even though none of our participants were likely to have had low language-learning aptitude, it raises the question of whether such low language-learning aptitude cultural early bilinguals differ from their high language-learning aptitude counterparts. This has been addressed by Archila-Suerte et al. (2018) in a study to identify the neuroanatomical bases of language-learning aptitude, (defined as "an innate, relatively fixed talent for learning languages"). Specifically, these investigators studied early bilingual children who were exposed to both languages early (Spanish from birth, and English at 5 years of age) and compared a group who had equal proficiency in Spanish and English with another group who did not reach proficiency in English commensurate with that of their Spanish proficiency (and not on par with the other group's proficiency in Spanish and English). They identified more GMV in caudate and putamen in those with equal proficiency in Spanish and English, compared to those with strong Spanish but weak English, suggesting that more GMV in these regions is associated with higher language-learning aptitude (since the learning environment for both groups was similar). Not surprisingly, these brain regions did not emerge in the results of the current study.

Our criterion for early bilinguals was learning both languages by or at age 6. The criterion for early bilingualism varies in the literature, and it is likely that the timing of language learning within this time window may affect brain and behavior. For example, Kousaie et al., (2021) found that simultaneous bilinguals (i.e. learning two languages from birth), early bilinguals (before 5 years of age), and late bilinguals (after 5 years of age) performed similarly on nonverbal and phonological working memory tasks. However, brain activity, while no different amongst the three groups for the nonverbal task, differed during the phonological working memory tasks, with the early bilinguals differing from the simultaneous and late bilingual groups. Similarly, there are several studies showing that infants who are exposed to bilingual environments in the first year of life show different patterns of attention than do infants in monolingual environments (Comishen et al., 2019; D'Souza et al., 2020; Kovács & Mehler, 2009; Weikum et al., 2007). These observations speak to the need for further fine-grained studies of different ages of acquisition within groups of early bilinguals and also longitudinal studies of bilingual children.

In the present study, our investigation is focused on a narrow section of the bilingual population, that is, those who are cultural and early bilinguals, are proficient in their two languages, and are users of Spanish and English. While this ensures we have a homogenous sample, it also means that we do not know how our results generalize to other bilinguals. Future studies need to determine if the results would be the same for early bilinguals with other attributes, specifically examining the effects of timing of learning both languages (e.g., simultaneous vs. age 6), orthographic depth (e.g., deep vs. shallow alphabetic languages), or writing systems (e.g., alphabetic vs. logographic). In addition, it would be beneficial for future studies to use continuous measures (e.g., for variables such as age and proficiency) rather than categorical comparisons (Luk & Bialystok, 2013) thereby taking the heterogeneity of the bilingual population into consideration.

4.5 | Main findings for the study of early bilingual children and adults

Our first important finding is that GMV is profoundly altered by the early bilingual experience. Generally, we observed far more differences in gray matter in our early bilinguals relative to monolinguals than those reported in the three prior studies of early bilingual adults. While Mechelli reported a difference in left and right inferior parietal cortex, Ressel et al. (2012) found no differences at the level of the whole brain (p > .05, family-wise error [FWE] corrected for multiple comparisons), only reporting differences in Heschl's gyrus based on an ROI analysis. Olulade et al. (2016), which included some of the same adults as the present study, reported between-group differences based on a whole-brain analysis primarily in bilateral frontal and right parietal regions. However, our sample size in the current study is significantly bigger than these prior studies in early bilinguals, with overall 46 early bilinguals and 76 monolinguals (children and adults combined), while Mechelli et al. (2004) had 25 early bilinguals and 25 monolinguals, Ressel et al. (2012) had 22 early bilinguals and 22 monolinguals and Olulade et al. (2016) had 15 early bilinguals and 15 monolinguals. Our overall sample size is also much larger than all prior studies on GMV differences in bilinguals (i.e., not only early bilinguals but also late bilinguals) that were included in the meta-analysis by Danylkiv and Krafnick (2020). From their Table 1, these studies in late bilinguals had overall sample sizes of 28, 39, 40, 40, 34, 38, and 46 while our sample size is 122 (for clarity, the three studies noted above on early bilinguals are not included in these numbers, although they are included in the original Table 1). Nevertheless, future studies would benefit from even larger sample sizes. We also used the most recent version of SPM (SPM12) to conduct VBM. Unlike prior studies, we also ensured that our results were not confounded by reading ability or SES.

Interestingly, our results are complex, with the effect of an early dual-language experience on GMV being extensive in children as well as in adults and resulting in areas of more GMV and areas of less GMV in early bilinguals than monolinguals. Studies of experience-dependent plasticity typically focus on the association between more experience/better performance with greater GMV; however, there is also evidence of relationships between more experience and less GMV in the same studies, indicating the complexities of the effects of experience. One notable example is Maguire et al.'s (2006) finding of more GMV in the posterior hippocampus together with less GMV in the anterior hippocampus of taxi drivers compared to bus drivers.

Our second important finding is that these effects on GMV following an early bilingual experience already manifest robustly in children. We found some, but not many areas where age played a modulating role in the effect of early bilingualism on GMV. The interaction analysis revealed no regions that followed a pattern that supported an effect of duration of experience. For most regions, the interactions came about because the regular pattern of development (usually more GMV in children than adults) was not followed by the monolinguals in these small islands of cortex (in pockets within areas of cortex that did differ as a function of age), in many cases leading to antagonistic effects. Generally, these regions were relatively small compared to the extent of those differences overall between early bilinguals and monolinguals (main effect of Language Background) and especially small when considering the vast difference overall between children and adults (main effect of Age Group). So, while our findings from the interaction analysis speak to the idea that there are differences in GMV between early bilinguals and monolinguals observed during childhood that are not observed in adults, these regions are few, and they are relatively small in size. Our results are important as they demonstrate altered brain anatomy in children as a consequence of early bilingualism, with little further change into adulthood; and some areas of more GMV, but also regions of less GMV in bilingual relative to monolingual children. These may have implications for their development of language skills and EC, which are important for academic success and daily functions. Interestingly, regions found to differ in early bilinguals in the current study have also been shown to differ in dyslexia (left superior temporal gyrus, left supramarginal gyrus, and left supplementary motor area) and in ADHD (left precentral gyrus and left supplementary motor area). Our results indicate that investigators should consider the language background of their participants in studies of dyslexia or ADHD.

5 | CONCLUSION

We found more GMV in Spanish–English early bilingual children compared to monolingual children in brain regions known to be involved in EC, and less GMV in bilingual children in regions associated with language. This pattern was largely upheld when combining children and adults with bilingual or monolingual backgrounds, with only a few regions influenced by age. Specifically, there were no age-dependent differences in bilinguals that indicated an effect of longer duration of the dual-language experience (for adults relative to children) on GMV; while there were indications of the reverse (i.e., a bigger difference in children relative to adults) most were not aligned with regions known to be involved in EC. Together, these findings show that GMV differences associated with early bilingualism manifest robustly in childhood, with relatively little divergence into young adulthood.

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CONFLICT OF INTEREST

None declared.

DATA AVAILABILITY STATEMENT

The MRI data acquired for this study were analyzed using the following publicly available software/toolboxes: the Statistical Parametric Mapping (SPM)12 toolbox (https://www.fil.ion.ucl.ac.uk/spm/) (Friston et al., 1994); MarsBaR toolbox (https://marsbar-toolbox.github.io) (Brett et al., 2002); label4MRI package (https://github.com/yunshiuan/label4MRI); and Jamovi (https://www.jamovi.org).

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