


RESEARCH ARTICLE

Functional neuroanatomy of arithmetic in monolingual and bilingual adults and children

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Abstract

Prior studies on the brain bases of arithmetic have not focused on (or even described) their participants' language backgrounds. Yet, unlike monolinguals, early bilinguals have the capacity to solve arithmetic problems in both of their two languages. This raises the question whether this ability, or any other experience that comes with being bilingual, affects brain activity for arithmetic in bilinguals relative to monolinguals. Here, we used functional magnetic resonance imaging to compare brain activity in 44 English monolinguals and 44 Spanish-English early bilinguals, during the solving of arithmetic problems in English. We used a factorial design to test for a main effect of bilingual Language Experience. Based on the known modulating roles of arithmetic operation and age, we used two arithmetic tasks (addition and subtraction) and studied two age groups (adults and children). When collapsing across operations and age, we found broad bilateral activation for arithmetic in both the monolingual group and the bilingual group. However, an analysis of variance revealed that there was no effect of Language Experience, nor an interaction of Language Experience with Operation or Age Group. Bayesian analyses within regions of interest chosen for their role in arithmetic further supported the finding of no effect of Language Experience on brain activity underlying arithmetic. We conclude that early bilingualism does not influence the functional neuroanatomy of simple arithmetic.

KEYWORDS

adults, bilingualism, children, fMRI, mathematics

1 | INTRODUCTION

Arithmetic is a critical academic and life skill. As such, there have been significant efforts to understand the factors that contribute to the successful acquisition of arithmetic (Duncan et al., 2007; National Mathematics Advisory Panel, 2008) and to characterize its neural correlates (Arsalidou, Pawliw-Levac, Sadeghi, & Pascual-Leone, 2018;

Arsalidou & Taylor, 2011; Peters & De Smedt, 2018). However, prior neuroimaging studies have not taken into consideration the potential role of bilingualism, even though sustained bilingual language experiences are prevalent across the globe (Crystal, 2012; Grosjean, 2010; Tucker, 1998). Instead, our current knowledge about the brain bases of arithmetic is largely derived from studies where participants' language backgrounds are not specified. To illustrate this point, of the 56 functional magnetic resonance imaging (fMRI) studies cited in recent meta-analyses and reviews of arithmetic in adults and children

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(Arsalidou et al., 2018; Arsalidou & Taylor, 2011; Peters & De Smedt, 2018), only four explicitly mentioned whether their participants were monolingual (two studies) or bilingual (two studies). This observation means that over 90% of studies may have included some or many participants who are bilingual. Bilingual individuals in these studies will likely have been capable of performing the same arithmetic task in another language, particularly those with early use of their two languages. While arithmetic performance may be the same for bilinguals and monolinguals, the neural substrates recruited may differ. This raises the question whether the inclusion of bilingual participants influences the results of these brain imaging reports and subsequent meta-analytic results. In this study, we addressed this important question by examining whether early bilingual language experience influenced brain activity during arithmetic.

1.1 | Possible role of the bilingual language experience on arithmetic

While some behavioral studies show differences in arithmetic performance between monolinguals and bilinguals (Daubert & Ramani, 2019; Hartanto, Yang, & Yang, 2018), others do not (Bialystok & Codd, 1997; Goldman, Negen, & Sarnecka, 2014; Sarnecka, Negen, & Goldman, 2017). Yet, there are several reasons why the bilingual language experience could produce differences in the neurofunctional bases of arithmetic. One is that bilinguals have extensive and routine experience managing two language systems that are always mentally “active,” and it has been argued that juggling two languages in this way may affect executive functions (i.e., skills that are needed to guide and control thoughts and actions). Indeed, prior literature has shown that some executive function skills are stronger in bilinguals compared to monolinguals (e.g., inhibitory control, attention, working memory, and shifting; Bialystok, 2017; Bialystok, Craik, Green, & Gollan, 2009; Bialystok, Craik, & Luk, 2012; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Valian, 2015). However, not all behavioral studies have found such an effect (Blom et al., 2017; Bonifacci et al., 2011; Dick et al., 2019; Engel de Abreu, 2011; Lehtonen et al., 2018; Nichols, Wild, Stojanoski, Battista, & Owen, 2020; Paap, 2019; Ratiu & Azuma, 2015). Another body of research has found executive function skills are important predictors of arithmetic, indicating a role for executive function skills like working memory in arithmetic (Best, Miller, & Naglieri, 2011; Bull & Lee, 2014; Cragg & Gilmore, 2014; DeStefano & LeFevre, 2004; Friso-Van Den Bos, Van Der Ven, Kroesbergen, & Van Luit, 2013; Peng, Namkung, Barnes, & Sun, 2015; Raghobar, Barnes, & Hecht, 2010; Yeniad, Malda, Mesman, Van Ijzendoorn, & Pieper, 2013). Integrating these two disparate lines of work leads to the possibility that bilinguals may be equipped differently when it comes to tackling arithmetic tasks by having stronger executive function skills. While the literature has been dominated by studies examining how executive functions are purportedly bolstered by the bilingual experience, similar evidence exists for phonological processing (i.e., processing language at the level of the sound unit), which is also thought to be stronger in bilinguals (for reviews, see Barac, Bialystok,

Castro, & Sanchez, 2014; Wren, Hambly, & Roulstone, 2013). Similar to executive function skills, phonological processing skills also predict arithmetic abilities, indicating a role for phonological retrieval during arithmetic (De Smedt & Boets, 2010; De Smedt, Taylor, et al., 2010; Fuchs et al., 2006; Hecht, Torgesen, Wagner, & Rashotte, 2001; Vukovic & Lesaux, 2013). Together, these findings raise the question whether cognitive adaptations in bilinguals result in different brain activity in bilinguals compared to monolinguals when engaging in arithmetic.

Relationships between bilingualism, executive function, phonological processing, and arithmetic are also found in neuroimaging studies, even though no studies have directly compared monolinguals and bilinguals during arithmetic. Generally speaking, arithmetic recruits a bilateral fronto-parietal network, including the superior parietal lobules, intraparietal sulci, inferior parietal lobules, hippocampi, occipito-temporal regions, as well as middle and inferior frontal gyri (Arsalidou et al., 2018; Arsalidou & Taylor, 2011). Activity in these regions is modulated by operation and age (see Peters & De Smedt, 2018). This fronto-parietal arithmetic network overlaps with some of the same brain regions shown to differ in brain function between monolinguals and bilinguals (for reviews see: Costa & Sebastián-Gallés, 2014; Grundy, Anderson, & Bialystok, 2017; Pliatsikas, 2020; Pliatsikas & Luk, 2016). Notably, regions that differ between monolinguals and bilinguals tend to be associated with executive control (e.g., dorsolateral and ventrolateral prefrontal, anterior cingulate, and inferior and superior parietal cortices; Bialystok et al., 2012), and some of the regions are also involved in phonological retrieval (left parietal and inferior frontal brain regions). Taken together, the overlap between brain regions that differ between monolinguals and bilinguals and those recruited for executive function, phonological retrieval, and arithmetic suggests that the bilingual experience could impact the functional anatomy of arithmetic in a number of ways. This underscores the need to compare brain activity in monolinguals and bilinguals during arithmetic processing, which was the goal of the current study. To help shed light on the mechanisms that might be at play, we used two distinct arithmetic tasks that are thought to differentially rely on executive function and phonological retrieval, as discussed next.

1.2 | Brain activity is modulated by the nature of the arithmetic task

Some arithmetic operations, such as subtraction and division, tend to be solved with calculation-based strategies like counting or transformation (Barrouillet, Mignon, & Thevenot, 2008; Campbell & Xue, 2001; Siegler, 1996). In contrast, operations such as addition and multiplication tend to rely more on language-mediated fact retrieval, particularly for arithmetic problems with small numbers (Imbo & Vandierendonck, 2008). Functional MRI studies have also shown calculation- and retrieval-based arithmetic recruit different brain regions: calculation recruits bilateral frontal and parietal regions and retrieval recruits left-lateralized inferior frontal and parietal regions

(Cho, Ryali, Geary, & Menon, 2011; De Smedt, Holloway, et al., 2010; Evans, Flowers, Luetje, Napoliello, & Eden, 2016; Grabner et al., 2009; Polspoel, Peters, & De Smedt, 2017; Prado et al., 2011; Tschentscher & Hauk, 2014; Yang et al., 2017). Importantly, brain regions involved in calculation-based arithmetic tend to overlap with those for executive control (right middle frontal gyrus, bilateral intraparietal sulci, right superior parietal lobule, and left temporo-parietal cortex; Matejko & Ansari, 2021; Zago et al., 2008), whereas regions involved in retrieval-based arithmetic overlap with those involved in phonological processing (left inferior frontal and temporo-parietal areas; Pollack & Ashby, 2017). The possible effects of bilingualism on executive control and/or language-based phonological retrieval motivated us to examine brain activity for operations that involved either calculation- or retrieval-based arithmetic. Specifically, we included subtraction (calculation-based) and addition (retrieval-based) tasks to investigate whether arithmetic operation played a modulating role in the potential differences between monolinguals and bilinguals (i.e., an interaction of bilingual language experience and operation).

1.3 | Age-related changes in brain activity

There is evidence that young bilingual children (ages 4–7) have relatively better numerical reasoning and arithmetic skills than monolingual children (Daubert & Ramani, 2019; Hartanto et al., 2018), although these differences do not hold up in all studies of bilinguals (Bialystok & Codd, 1997; Goldman, Negen, & Sarnecka, 2014; Sarnecka et al., 2017). Further, there is no evidence that older bilingual children, adolescents, or adults have better arithmetic skills than monolinguals. Therefore, if this effect is age specific, it is important to study adults and children. Age is also an important consideration when it comes to the neural bases of arithmetic processing. Behavioral studies have demonstrated that younger children's arithmetic processing is less automatized and involves more laborious strategies like counting, as opposed to the efficient retrieval of memorized arithmetic facts employed by adults (Barrouillet & Fayol, 1998; Caviola, Mammarella, Pastore, & LeFevre, 2018; Vanbinst, Ghesquiere, & De Smedt, 2014). Given this developmental trajectory of arithmetic processing, it has been of interest to determine whether brain activity during arithmetic differs between adults and children. Studies of arithmetic that included adults and children have found that activity in frontal brain areas decreases with greater age, while activity in parietal areas increases. This reflects an overall frontal to parietal shift over development as arithmetic processing becomes automatized and requires fewer frontal executive function resources (Chang, Metcalfe, Padmanabhan, Chen, & Menon, 2016; Davis et al., 2009; Evans et al., 2016; Kawashima et al., 2004; Kucian, Von Aster, Loenneker, Dietrich, & Martin, 2008; Rivera, Reiss, Eckert, & Menon, 2005; for reviews of the brain bases of arithmetic over development, see Peters & De Smedt, 2018; Zamarian, Ischebeck, & Delazer, 2009). Similarly, the neural bases for executive function (Klingberg, Forssberg, & Westerberg, 2002; Kwon, Reiss, & Menon, 2002; Luna, Padmanabhan, & O'Hearn, 2010) and phonological processing (Bitan et al., 2007) have been shown to change with

age. Therefore, an investigation into the brain bases of arithmetic in bilinguals could have different outcomes depending on whether adults or children are studied (i.e., an interaction of bilingual language experience and age group). Lastly, it has been suggested that the advantage for executive control in bilinguals is more pronounced in children than adults (Bialystok, Martin, & Viswanathan, 2005; Kroll & Bialystok, 2013; but see D'Souza, Moradzadeh, & Wiseheart, 2018; Paap, 2019) due to adults having reached peak executive function performance. For these reasons, both adults and children were included in the present study.

1.4 | Current study

When considered together, the behavioral and neuroimaging literature discussed above suggest that the brain bases for arithmetic processing in monolinguals and bilinguals may differ. Specifically, bilinguals have been shown in some studies to have relatively stronger executive function and phonological skills, which are both important for arithmetic. Further, there is spatial overlap between brain regions shown to differ in bilinguals (relative to monolinguals) and those underlying arithmetic, executive control, and language-related (phonological processing) functions. However, it has not been directly tested whether the neural underpinnings of arithmetic differ between monolinguals and bilinguals. The result has important repercussions for the interpretation of the existing corpus of studies on the neural signatures for arithmetic. The purpose of this study was therefore to compare brain activity during arithmetic processing in English monolingual and Spanish-English early bilingual participants. We predicted brain regions involved in calculation- and retrieval-based arithmetic (Peters & De Smedt, 2018) may both be affected by a bilingual language experience. Specifically, we anticipated that brain activity during arithmetic might differ in regions known to be involved in executive function (e.g., bilateral intraparietal sulci, superior parietal lobules, and middle frontal gyri), especially for calculation-based arithmetic (subtraction), which is thought to rely on executive control. At the same time, there is reason to expect differences between monolinguals and bilinguals in regions involved in phonological processing (e.g., in left temporo-parietal areas and the left inferior frontal gyrus), especially during retrieval-based arithmetic (addition) due to its reliance on language areas. We further explored whether differences between the monolingual and bilingual groups were modulated by age because arithmetic, executive control, and phonological processing undergo developmental changes, which could result in a more pronounced effect of bilingualism in children.

We studied 44 English monolinguals (25 adults and 19 children) and 44 Spanish-English early bilinguals (26 adults and 18 children). We first conducted two whole-brain one-sample *t*-tests to depict areas activated by arithmetic in monolingual and bilingual groups separately (averaging over both operations and both age groups). Next, we used a whole-brain $2 \times 2 \times 2$ mixed factorial analysis of variance (ANOVA; Language Experience, Operation, Age Group) to test for a main effect of Language Experience, as well as interactions between

Language Experience and Operation, and Language Experience and Age Group. Last, we interrogated 14 regions of interest (ROIs) in the arithmetic network (seven in each hemisphere) using Bayesian analyses to examine the strength of evidence for the null versus alternative hypotheses.

2 | METHODS

2.1 | Participants

Participants were 25 English monolingual adults (aged 18–29 years), 19 English monolingual children (aged 6–12 years), 26 Spanish-English bilingual adults (aged 18–28 years), and 18 Spanish-English bilingual children (aged 7–12 years), all recruited from the greater Washington, D.C. Metropolitan Area (Table 1). Age was similar for monolingual and bilingual children, as well as bilingual and monolingual adults: an ANOVA examining the effects of age between groups revealed no main effect of Language Experience (Monolingual/Bilingual) ($F_{(1,84)} = .48, p = .49$), nor an interaction between Language Experience and Age Group (Adults and Children) ($F_{(1,84)} = .02, p = .89$); there was, necessarily, a main effect of Age Group, $F_{(1,84)} = 342.5, p < .001$. Likewise, the sex distribution among the groups was not significantly different ($\chi^2 [3, N = 88] = 4.88, p = .18$). Handedness was assessed (in English) with the Edinburgh Handedness Test (Oldfield, 1971). All participants were right-handed except for three bilingual children who were left-handed. To exclude participants with math-based learning disabilities, mathematical abilities were evaluated for screening purposes (in English) using the Woodcock Johnson III Tests of Achievement Calculation subtest (Woodcock, McGrew, & Mather, 2001). All had standard scores greater than 85, indicating that their math abilities fell within or above the normal range.

All adult participants, monolinguals, and bilinguals, had graduated high school and were either enrolled in an undergraduate program or had completed a bachelor's degree (or higher) at the time of participation. Among the children, all of their parents had graduated from high school and the great majority (95%) had attended college, with 88% having completed a college degree, and this distribution was equal between the parents of monolingual and bilingual children. Bilingual participants learned both Spanish and English prior to the age of six, using both daily. They had minimal exposure to a third additional language, except one bilingual child who had a parent who spoke Portuguese at home. As is common in bilingual research, we used a questionnaire to gauge the competence of the bilinguals' two

languages as described in Meschyan & Hernandez (2006). Adult bilingual participants rated their listening, speaking, reading, and writing skills in both languages on a scale of 1 (low competence) to 7 (native-like). For bilingual children, a parent made this assessment for their child. The overall score across all four measures in the bilingual groups was a 6.6 for English and a 6.2 for Spanish (adults and children combined), indicating high competence in both languages.

All experimental procedures were approved by the Institutional Review Board at Georgetown University. Written informed consent was obtained from all participants aged 18 years or older; for participants younger than 18, parental written consent was obtained in addition to verbal and written assent from the child. Several monolingual participants (15 adults and 12 children) were previously included in a study examining the role of age on the neural bases of arithmetic (Evans et al., 2016).

2.2 | Digit span

Though we did not use a battery of executive function or working memory measures, we tested working memory (in English) using the Digit Span (WAIS-III for adults, WISC-III for children; Wechsler, 1991, 1997). The Digit Span is a standardized measure that gauges a person's ability to repeat a recently heard string of numbers, both forward and backward. This test allowed us to compare working memory in our monolingual and bilingual participants, and to examine the relationship between working memory and math skills (Adesope, Lavin, Thompson, & Ungerleider, 2010; Bull & Lee, 2014; Cragg & Gilmore, 2014; Daubert & Ramani, 2019; DeStefano & LeFevre, 2004; Grundy & Timmer, 2017; Hartanto et al., 2018). Specifically, we conducted a post-hoc 2×2 ANOVA to test for a main effect of Language Experience, as well as for an interaction between Language Experience and Age Group on Digit Span (note: Digit Span data were missing for 1 monolingual adult and 2 monolingual children). We also conducted Pearson's correlations for the entire sample between Digit Span and the Woodcock Johnson III Tests of Achievement Calculation subtest (Woodcock et al., 2001).

2.3 | In-scanner arithmetic task

In the MRI scanner, participants completed two runs of a single-digit arithmetic verification task. This task has been used in prior studies examining the functional brain bases of arithmetic (Evans et al., 2014,

TABLE 1 Demographic characteristics

	Monolinguals		Bilinguals		p-value
	Adults	Children	Adults	Children	
N sex (F/M)	25 (11F/14M)	19 (8F/11M)	26 (18F/8M)	18 (11F/7M)	n.s.
Avg. age in years (age range)	21.8 (18.7–29.2)	9.4 (6.8–12.8)	22.1 (18.4–28.6)	9.9 (7.7–12.6)	n.s.

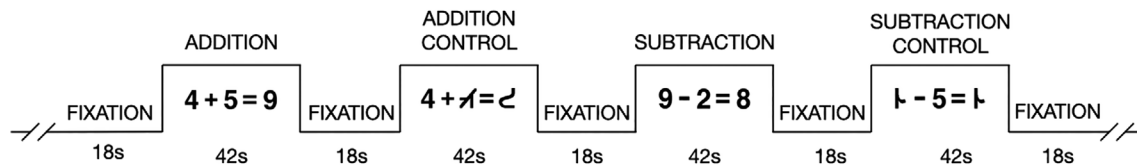


FIGURE 1 Schematic of one run of the fMRI math task, reflecting alternating blocks of fixation, task, and active control conditions

2016) and was adapted from similar tasks used by others (Rivera et al., 2005). A schematic of one run of the task is depicted in Figure 1. Prior to entering the MRI scanner, participants received training on the task with paper stimuli, then on a computer screen, and finally in a mock scanning environment. The training was reinforced until participants were comfortable with the task and able to perform it successfully. For the arithmetic task, participants solved visually presented addition or subtraction problems consisting of Arabic digits (e.g., $3 + 5 = 8$; $9 - 3 = 6$) and responded with a left/right hand button press to indicate whether the provided solution was correct or incorrect. Incorrect solutions deviated from the correct answer by a value of 1. For the active control task for both addition and subtraction, one digit on each side of the equal sign was replaced with pseudofont characters. Participants were asked to indicate whether these two pseudofont characters were the same or different (e.g., $3 + \square = \square$; $2 - 2 = \square$). In all conditions, half of the stimuli were correct. Bilingual participants were asked to think in English while completing the task, an instruction that was reinforced by reminders delivered in English before each run. Participants completed further tasks in Spanish during their visit, but the English math scans were embedded in an imaging session with another task (single word processing) conducted in English.

The task was executed with the software Presentation using a block-design. Each of the two runs consisted of unique problems such that no problems repeated between runs. The order of the runs was counterbalanced across participants and randomized at the outset of the study. One block of each task (Addition, Addition Active Control, Subtraction, and Subtraction Active Control) was presented per run. Each block contained 10 stimuli and was 42 s in duration. Each stimulus was presented on the screen for 3,000 ms, followed by a 1,200 ms interstimulus interval during which a fixation cross was presented. Participants could respond while the problem was being presented, or during the interstimulus interval. There were passive Fixation blocks of 18 s duration prior to and following each of the task blocks. The beginning of each run also had an additional 6 s of fixation to allow for saturation effects, and the end of the run had an additional 3 s to allow the hemodynamic response function to return to baseline (resulting in a total fixation period of 24 s at the beginning and 21 s at the end). Together, the entire run lasted 4 min and 27 s.

Runs from any participant who scored less than 50% (representing chance levels in this two-alternative task) on Addition and Subtraction trials combined were excluded from analyses. One run from a monolingual child and one run from two bilingual children were excluded for this reason. In these three cases, the remaining run from the participant was entered into analyses. No participants scored less

than 50% on the arithmetic (pseudofont) active control task. Reaction time data were also collected for later analyses. Accuracy and reaction time were scored such that if participants made two responses we took the second response, and reaction time was measured from the start of the trial to the time of the second response. In-scanner performance data were missing for one monolingual adult, one monolingual child, and one bilingual adult.

Accuracy and reaction time data from the in-scanner math tasks (averaging across those runs included) were submitted to a $2 \times 2 \times 2$ mixed factorial ANOVA to parallel the factorial fMRI analysis, with Language Experience (Monolinguals vs. Bilinguals) and Age Group (Adults vs. Children) as between-subjects factors and Operation (Addition vs. Subtraction) as a within-subjects factor. Analyses were conducted using the open statistical software program *jamovi*, version 1.1.9.0 (the jamovi project, 2020) and main effects and interactions were considered statistically significant at $p < .05$.

2.4 | fMRI acquisition and preprocessing

Whole head echo-planar images (EPI) were collected on a 3.0-Tesla Siemens Magnetom Tim Trio scanner at the Center for Functional and Molecular Imaging at Georgetown University Medical Center with the following parameters: TR of 3,000 ms, TE of 30 ms, 64×64 matrix, 192 mm FOV, flip angle = 90° , 50 axial slices collected in a descending sequence, $3.0 \times 3.0 \times 2.8$ mm voxels with a 0.2 mm gap. For each functional run, 89 full 3D brain volumes were collected. High-resolution T1-weighted structural brain images were also collected, for the purpose of coregistering the functional images.

2.5 | fMRI analysis

Preprocessing and first level analyses were conducted using SPM12 (Statistical Parametric Mapping, 2020). Preprocessing involved removal of the first five volumes of each run to account for T1 saturation effects. The remaining volumes were corrected for slice timing and then for motion deviations within each run. Any run in which a participant's motion deviated more than 1.5 mm in more than 10% of volumes (measured from one volume to the next) was removed from analyses. Three runs from monolingual children, three from bilingual adults, and two from bilingual children were excluded for this reason. In cases where a run was removed for a given participant, the remaining run was included in analyses. Further, volumes exceeding the 1.5 mm threshold were censored and 6 motion parameters

representing movement in the roll, pitch, yaw, x, y, and z directions were entered as regressors in functional analyses. A threshold of more than a 5% deviation in global signal was additionally used as an exclusion criterion; no runs from any participant exceeded this threshold. Motion-corrected (realigned) images were then coregistered to each participant's high-resolution structural image. Finally, images were normalized to the standard Montreal Neurological Institute (MNI) EPI template and smoothed using an 8 mm^3 full width half maximum Gaussian kernel. Functional images from all participants were normalized to the adult template, in accordance with prior published work comparing the functional neuroanatomy of arithmetic in adults and children (Evans et al., 2016). Images underwent careful visual inspection to ensure that they were free of neural abnormalities or artifacts, and to verify that each preprocessing step was executed successfully.

2.6 | Brain imaging analyses

2.6.1 | Whole-brain within-group maps for arithmetic in monolinguals and bilinguals (age groups and operations combined)

We first generated within-group maps of brain activity during arithmetic, separately in Monolinguals and Bilinguals (collapsed across age groups and operations). Both of the active arithmetic tasks were compared to the active control tasks (i.e., [Addition + Subtraction] > [Addition Active Control + Subtraction Active Control]), and within-group maps were generated using one-sample *t*-tests implemented in SPM12 (Statistical Parametric Mapping, 2020). A height threshold of $p < .001$ and a false-discovery rate (FDR) cluster-level extent threshold of $p < .05$ were used. Data were visualized using MRICroGL (Rorden, 2019).

2.6.2 | Whole-brain mixed factorial ANOVA

To address the role of bilingual Language Experience we conducted a $2 \times 2 \times 2$ mixed factorial ANOVA implemented in SPM12 (Statistical Parametric Mapping, 2020) with Language Experience (Monolinguals vs. Bilinguals) and Age Group (Adults vs. Children) as between-subjects factors and Operation (Addition vs. Subtraction) as a within-subjects factor. First, we examined the main effect of Language Experience, followed by interactions of Language Experience \times Operation, and Language Experience \times Age Group. We first performed the ANOVA contrasting the Addition and Subtraction tasks with the active control tasks (i.e., Addition > Addition Active Control; Subtraction > Subtraction Active Control). We also performed a second ANOVA, this time contrasting the Addition and Subtraction tasks with the low-level Fixation condition (i.e., Addition > Fixation; Subtraction > Fixation). This second analysis provided a check in case the children process the active control tasks differently than the adults, in which case age-related differences in brain activity during arithmetic could be due to the active control task rather than the arithmetic tasks

per se (Church, Petersen, & Schlaggar, 2010). A height threshold of $p < .005$ and an FDR cluster-level extent threshold of $p < .05$ were used.

While these ANOVAs were executed at the level of the whole brain, we also conducted a post hoc analysis within 14 ROIs that are known to be involved in arithmetic. For a detailed description of the methods of this analysis, please see Supporting Information.

2.6.3 | Bayesian region of interest analyses

In addition to the frequentist statistical tests described above, we conducted a post hoc Bayesian mixed factorial ANOVA (Rouder, Morey, Speckman, & Province, 2012). For this analysis, we contrasted the mean signal change for the Addition and Subtraction tasks relative to Fixation. This was done in the same 14 ROIs known to be involved in arithmetic noted above. These regions were selected based on a review by Peters and De Smedt (2018) on the functional correlates of arithmetic in adults and children. Specifically, we took those brain regions depicted in Figure 1 of the Peters and De Smedt review: left and right hemisphere hippocampi, superior parietal lobules, intraparietal sulci, angular gyri, supramarginal gyri, inferior frontal gyri, and middle frontal gyri. These regions are listed in Table 2 according to their role in calculation- or retrieval-based arithmetic described by Peters and De Smedt (2018). To capture these regions, masks were generated using the Anatomy Toolbox (Eickhoff et al., 2007) for all ROIs except the middle frontal gyrus, which was created using the Harvard-Oxford Atlas in FSL (version 6.0), and removing any overlap with the inferior frontal gyrus ROI. Mean signal was extracted from each ROI (7 homotopic regions in each hemisphere using MarsBaR version 0.44; Brett, Anton, Valabregue, & Poline, 2016). We used the beta values of the general linear model for the arithmetic tasks versus fixation. The analyses were conducted using the "jsq" module in the open statistical software program *jamovi*, version 1.1.9.0 (the jamovi project, 2020). We used a Bayesian ANOVA (using the default Cauchy prior) to establish evidence for the null hypothesis versus the alternative hypothesis.

TABLE 2 Left and right hemisphere regions of interest used in the analyses based on a review by Peters and De Smedt (2018)

Regions of interest (ROI)	Arithmetic process
1. Hippocampi (HC)	Retrieval
2. Superior parietal lobules (SPL)	Calculation
3. Intraparietal sulci (IPS)	Calculation
4. Angular gyri (AG)	Retrieval
5. Supramarginal gyri (SMG)	Retrieval
6. Inferior frontal gyri (IFG)	Retrieval/calculation
7. Middle frontal gyri (MFG)	Calculation

Note: The fusiform gyrus was not included in our analysis because its role is not specific to calculation- or retrieval-based arithmetic.

3 | RESULTS

3.1 | Digit span

In a 2×2 ANOVA (Language Experience and Age Group as between-subjects factors), there was a main effect of Language Experience ($F_{(1,81)} = 4.27, p = .042$), and main effect of Age Group ($F_{(1,81)} = 6.15, p = .015$), where monolinguals had higher standard Digit Span scores than bilinguals, and adults had higher standard Digit Span scores than children. There was no interaction between Language Experience and Age Group. In the group as a whole ($n = 85$), we found that Digit Span was positively correlated with Calculation ($r(83) = .36, p < .001$).

3.2 | In-scanner arithmetic task

Accuracy and reaction time scores for each task are reported in Table 3. A mixed factorial ANOVA was conducted to parallel the factorial fMRI analysis (Language Experience and Age Group as between-subjects factors, and Operation as a within-subjects factor). When examining accuracy, the ANOVA revealed no main effect of Language Experience, nor an interaction of Language Experience with Operation, or Language Experience with Age. Together, these results demonstrate no difference in accuracy that can be attributed to bilingualism. While less relevant, there were the following expected significant effects: a main effect of Operation ($F_{(1,81)} = 36.51, p < .001$, partial $\eta^2 = 0.31$), a main effect of Age Group ($F_{(1,81)} = 31.93, p < .001$, partial $\eta^2 = 0.28$) and an interaction between Operation \times Age Group ($F_{(1,81)} = 16.42, p < .001$, partial $\eta^2 = 0.169$). Post hoc *t*-tests revealed that, as anticipated, Addition problems were solved more accurately than Subtraction problems ($t(81) = 6.04, p < .001$) and Adults were more accurate than Children ($t(81) = 5.65, p < .001$), with the relatively greater accuracy of Addition over Subtraction being more pronounced for Children than for Adults.

The ANOVA for reaction time revealed a main effect of Language Experience ($F_{(1,81)} = 5.53, p = .021$, partial $\eta^2 = 0.064$), but no interaction of Language Experience with Operation, or Language Experience

with Age. Post hoc *t*-test revealed that monolinguals were faster than bilinguals ($t(81) = -2.35, p = 0.021$). The following were also significant, as expected: a main effect of Operation ($F_{(1,81)} = 87.51, p < .001$, partial $\eta^2 = 0.52$), a main effect of Age Group ($F_{(1,81)} = 108.06, p < .001$, partial $\eta^2 = 0.57$), and an interaction of Operation \times Age Group ($F_{(1,81)} = 5.74, p = .019$, partial $\eta^2 = 0.066$). Post hoc *t*-tests revealed that Addition was solved more quickly than Subtraction ($t(81) = -9.35, p < .001$), and adults were faster than children ($t(81) = -10.4, p < .001$), with the relatively greater speed on Addition compared to Subtraction problems being more pronounced for children than for adults.

3.3 | Whole-brain within-group maps for arithmetic in monolinguals and bilinguals (age groups and operations combined)

Activation for the Arithmetic $>$ Active Control contrasts (collapsed across operations and age groups) can be seen for the Monolinguals (top panel) and the Bilinguals (lower panel) in Figure 2, and Table 4. For either group, this activation spanned the bilateral inferior frontal gyri, bilateral posterior medial frontal cortices, right insula, left intraparietal sulcus, and left precentral gyrus.

3.4 | Whole-brain mixed factorial ANOVA

The mixed factorial ANOVA, using the contrast of Arithmetic $>$ Active Control tasks, revealed no main effect of Language Experience, and no interactions between Language Experience and Operation, or Language Experience and Age Group. When the ANOVA was repeated using the Fixation baseline (instead of the Active Control tasks), it yielded the same outcome. Lastly, another ANOVA was conducted within a mask of 14 ROIs selected a priori based on their known involvement in arithmetic and this also revealed no main effect of Language Experience, or an interaction of Language Experience with Operation, or Language Experience with Age Group.

TABLE 3 Performance on in-scanner arithmetic task

		Monolinguals		Bilinguals	
		Adults	Children	Adults	Children
Addition	Accuracy (SD)	99.6% (1.4)	93.3% (8.7)	99.2% (1.9)	89.2% (15)
	RT (SD)	995 ms (135)	1,760 ms (479)	1,197 ms (227)	1,913 ms (555)
Addition control	Accuracy (SD)	98.8% (4.2)	98.6% (2.9)	98.2% (4.5)	95.8% (7.1)
	RT (SD)	919 ms (123)	1,258 ms (187)	1,010 ms (154)	1,390 ms (272)
Subtraction	Accuracy (SD)	98.8% (3.4)	84.7% (20)	96.2% (5.8)	78.3% (18)
	RT (SD)	1,183 ms (197)	2,159 ms (525)	1,457 ms (317)	2,271 ms (568)
Subtraction control	Accuracy (SD)	98.5% (2.3)	96.7% (5.4)	93.8% (9.5)	92.2% (11)
	RT (SD)	946 ms (150)	1,271 ms (218)	1,053 ms (186)	1,358 ms (309)

Note: Accuracy (percentage correct), reaction time (RT; in milliseconds), and their standard deviations are reported, separated by Language Experience and Age group.

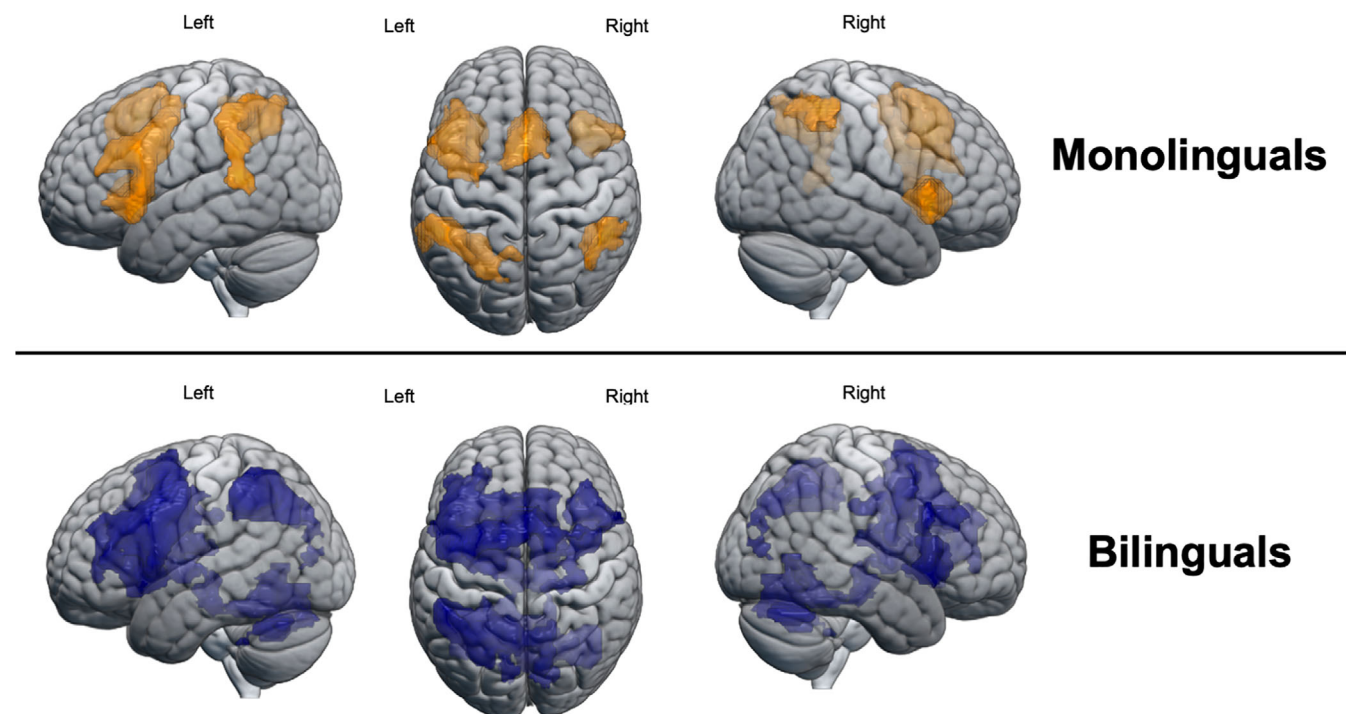


FIGURE 2 Group maps for brain activity during arithmetic (compared to the active control task) in monolinguals (yellow) and bilinguals (blue), collapsed across operations and age groups (height threshold $p < .001$, FDR $p < .05$)

TABLE 4 Anatomical locations and MNI coordinates of significant activation for the contrast of task > active control task, separately for monolinguals and bilinguals (collapsed across age groups and operations)

Anatomical location	MNI coordinates			T-value	Cluster size
	x	y	z		
<i>Monolinguals (arithmetic > active control)</i>					
L insula	-30	22	-2	7.14	4,018
L inferior frontal gyrus					
L precentral gyrus					
R insula	40	20	2	6.75	1,308
R inferior frontal gyrus					
L/R posterior medial frontal cortex	-6	12	50	6.19	1,998
L/R medial cingulate cortex					
L intraparietal sulcus	-66	-46	14	5.25	2,139
L supramarginal gyrus					
L superior temporal gyrus					
L superior parietal lobule					
R intraparietal sulcus	52	-44	54	5.19	675
R supramarginal gyrus					
<i>Bilinguals (arithmetic > active control)</i>					
L precentral gyrus	-46	-2	40	7.38	17,975
L/R posterior medial frontal cortex					
L inferior frontal gyrus					
L middle frontal gyrus					
L/R anterior cingulate cortex					
L/R cerebellum (lobule VI, lobule V)					
L intraparietal sulcus	-26	-52	38	6.82	4,070
L/R precuneus					
R insula	30	22	-2	6.20	1,845
R inferior frontal gyrus					

Timmer, 2017; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Valian, 2015), which in turn may enhance arithmetic abilities (Daubert & Ramani, 2019; Hartanto et al., 2018). However, the evidence for a “bilingual advantage” in executive function is controversial, with a number of studies showing no such effect (Dick et al., 2019; Lehtonen et al., 2018; Nichols et al., 2020). As a result, some have argued that differences in executive function between monolinguals and bilinguals do not exist (Antón, Carreiras, & Duñabeitia, 2019; Dick et al., 2019; Duñabeitia et al., 2014; Gathercole et al., 2014; Lehtonen et al., 2018; Nichols et al., 2020; Paap, 2019; Paap et al., 2017; Paap, Johnson, & Sawi, 2015, 2016; Paap, Sawi, Dalibar, Darrow, & Johnson, 2014; von Bastian, Souza, & Gade, 2015).

A range of factors could explain the conflicting findings in the behavioral studies comparing executive function in bilinguals and monolinguals. There are general methodological factors, such as poorly matched groups and the use of small sample sizes. Different studies employed different measures of executive function, making it difficult to compare between studies and also raising the possibility that a between-group difference is only found for some measures of executive function, but not others (Kroll & Bialystok, 2013). The specific bilingual experience of participants has also been discussed, with some arguing that cognitive advantages may depend on factors such as daily usage and proficiency in each language (Kroll & Bialystok, 2013; Luk & Bialystok, 2013), with advantages of the bilingual experience only being conferred if it involves extensive managing of both languages (Macnamara & Conway, 2014). As already noted, the bilingual advantage in executive function may only be observed at certain life stages and not others, specifically manifesting when participants are not at their cognitive peak, such as in young children or older adults (Bialystok et al., 2005). Others have proposed that bilinguals only recruit domain-general executive function skills when they are learning their two languages, after which they progress from this state of controlled processing to one of automatic processing (Paap, 2018). These experimental issues will require further investigation in future behavioral studies.

While we did not measure a range of executive function skills, we did measure working memory on the Digit Span task and did not find bilinguals were better than monolinguals, rather, we found that monolinguals outperformed bilinguals. A recent study in adult monolinguals and bilinguals measured working memory using the Digit Span as part of a broad battery of 12 cognitive tasks (Nichols et al., 2020), and they reported a range of results. When the two groups were carefully matched on age, education, gender, socioeconomic status, and handedness, frequentist statistics suggested no difference between monolinguals and bilinguals on Digit span, and Bayesian statistics indicated strong evidence in favor of no difference between the two groups. The same was the case for the other cognitive measures investigated. However, the same study by Nichols and colleagues reports results from a larger version of the sample, and in this case the groups were not matched for age, education, gender, socioeconomic status, and handedness. The comparison of the unmatched groups on Digit Span was mixed, with frequentist statistics indicating that

bilinguals performed better than monolinguals, and Bayesian statistics indicating strong evidence in favor of no difference between the groups. The unmatched bilingual and monolingual groups also had differences on several of the other cognitive tasks (monolinguals outperformed bilinguals on grammatical reasoning, feature matching, mental rotation, and token search), emphasizing the need to carefully matched groups in studies of bilingualism. Taken together with our own results, it appears that findings for a difference between monolinguals and bilinguals on the Digit Span are mixed.

Ultimately, the present study was focused on the brain bases of arithmetic, recognizing that activity may differ between bilinguals and monolinguals, irrespective of whether or not the bilinguals performed better on measures of executive function. In other words, our goal was not to test the larger theory of the bilingual advantage, but to inquire whether the bilingual experience may result in differences in how the bilingual brain processes arithmetic. This question is important because it has implications for interpreting prior studies that did not attempt to control for such effects, and for participant selection in future studies. The possibility that the bilingual experience conveys cognitive advantages would be one reason to expect such differences. Our study is the first to specifically examine the brain bases for arithmetic in bilinguals compared to monolinguals and we did not find differences, thereby alleviating concerns about whether the bilingual experience may affect the brain systems involved in simple arithmetic processing.

4.2 | Arithmetic performance in bilinguals and monolinguals

While there were no differences in accuracy on the Addition and Subtraction tasks inside the scanner, there were some reaction time differences between the monolingual and bilingual groups. The presence of a main effect of language experience on reaction time on the math tasks (and, as discovered by further testing, also on the active control tasks involving pseudofont character matching) suggests that our monolinguals were globally faster compared to our bilinguals (i.e., not specifically faster on arithmetic problems). The literature on differences in arithmetic processing speed between monolinguals and bilinguals is mixed. A prior study comparing adult Spanish-English bilinguals to English monolinguals did not find reaction time differences during a simple addition verification task (Geary, Cormier, Goggin, Estrada, & Lunn, 1993), nor did a study comparing German-Swedish adolescent/young adult bilinguals to German monolinguals on a written production task of simple arithmetic (Mägiste, 1980). Consistent with our findings, Marsh and Maki (1976) found faster reaction time in English adult monolinguals compared to English-Spanish bilinguals, as did McClain and Huang (1982). However, McClain and Huang (1982) also found that this difference disappeared when bilinguals completed their English and Spanish experimental sessions on different days. Thus, it is possible that completing the task in both languages within a visit (though not within the same fMRI run) may explain differences in reaction times between monolinguals and

bilinguals for the arithmetic task and its active control task. The relatively faster monolingual reaction time on the tasks may be attributable to the additional cognitive demands placed on the bilinguals during the English scan session (i.e., to think specifically in English when they had another language available for use; a requirement not imposed on the monolinguals). Ultimately, the difference in global reaction time is not likely to account for our brain imaging results of no between-group differences.

4.3 | No effect of bilingual language experience on the brain bases of arithmetic

Null findings in the field of bilingual research are often conceived of as less interesting. Indeed, publication bias has been identified in the field of bilingual studies: conference presentations reporting an advantage in bilinguals are ultimately more likely to be published in journals relative to the conference presentations reporting no advantage (de Bruin, Treccani, et al., 2015). Our results naturally raise questions about whether the negative finding can be attributed in any way to the experimental procedures used in our study. We will examine this question from the perspective of the participant group, arithmetic task, and analyses used.

One concern in bilingual studies is whether the participants are early, balanced bilinguals rather than second language learners. The bilinguals in this study are early bilinguals (having learned both languages prior to age 6) with high proficiency, and are therefore relatively balanced in their use of their two languages. Further, they are also bicultural, having learned Spanish and English as part of their upbringing. This is important because it means that they acquired two languages as a result of their life circumstances, as opposed to those who excel at second language learning, perhaps as a result of having strong executive function skills (Bialystok et al., 2012; MacNab, 1979; Valian, 2015). Furthermore, bicultural individuals experience yet another dimension on which they must switch between (cultural) representations (Grosjean, 2010; Treffers-Daller, Ongun, Hofweber, & Korenar, 2020), potentially further enhancing their executive function abilities and corresponding brain areas. If bilingualism yields effects on the brain system for arithmetic, potentially as a consequence of its effects on executive function, our population was an optimal one to test this. Here, it is important to also highlight that our participant groups had similar socioeconomic status, which has been criticized as a confounding factor in comparisons of monolinguals and bilinguals (de Bruin, Bak, et al., 2015; MacNab, 1979; Swain & Cummins, 1979). While this study focused on the most common language combination in the United States (Spanish-English), examining a broader range of language pairings could prove informative for the potential role of language experience in shaping the brain networks for arithmetic.

It is important to point out that we included children as well as adults to address the issue of age in the bilingual literature. At the same time, it must be acknowledged that our children are older than those included in some behavioral studies comparing monolinguals and bilinguals. Studies that show a bilingual advantage in arithmetic

are based on younger children (Daubert & Ramani, 2019; Hartanto et al., 2018), aged 4–7, which is younger than those studied here. Given their age, the tasks administered to children in some of these prior studies involved more basic numerical skills. On the other hand, other studies show young bilinguals to be equivalent to monolinguals on these kinds of tasks (Bialystok & Codd, 1997; Goldman, Negen, & Sarnecka, 2014; Sarnecka et al., 2017). It is therefore possible that the bilingual children in these studies and our study have reached the stage of automatic processing for arithmetic (such as navigating two language representations of a solution to an arithmetic problem). Alternatively, the children may be old enough that there are no measurable differences in executive function that would impact arithmetic. The inclusion of a group of younger children and/or participants in the early stages of acquiring a second language would be needed in order to fully explore these ideas.

Turning more specifically to our arithmetic tasks, we found robust activation in the monolingual as well as bilingual groups (Figure 2), consistent with other publications of arithmetic processing (Arsalidou et al., 2018; Arsalidou & Taylor, 2011; Peters & De Smedt, 2018) and our own prior studies using these tasks (Evans et al., 2014, 2016). While these arithmetic tasks have been successful in distinguishing between children with and without a learning disability (Evans et al., 2014), it is possible that they were not ideal for eliciting differences between monolinguals and bilinguals. For example, it may be that they were not sufficiently taxing to elicit a difference between the groups. It has been suggested that the bilingual advantage only emerges in situations where the demand for cognitive control is high (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009). Therefore, we have to consider the possibility that our tasks simply did not tap arithmetic processing to the extent that they revealed differences in activation between our monolinguals and bilinguals. Indeed, our tasks were deliberately designed to be simple enough to be performed by both adults and children at greater than chance levels. However, the behavioral results reveal a range of performances: while adults performed, on average, at very high levels of accuracy (in the 96–99% range), the children's average accuracy was significantly lower (in the 78–93% range). The lower performance in children indicates that for them the arithmetic tasks were more challenging, especially the subtraction task, as would be expected, yet there was no interaction between language experience and operation, or between language experience and age group to indicate that performance or brain activity was different between the monolingual and bilingual groups under these more difficult task conditions. Thus, the nature of the task does not seem to explain our findings. However, future research could examine this further by comparing monolinguals and bilinguals on a range of tasks, with some being more complex (such as multi-digit arithmetic or algebra) than others.

Another potential concern may be that the null results of this study could be related to the analytic procedures used. To this point, we used standard analysis procedures and widely accepted significance thresholds. We used a factorial design to address a potential role of arithmetic operation and chronological age. We also used Bayesian analyses (Rouder et al., 2012) which have been argued to

have advantages over the traditionally used *p*-value (Dienes, 2014; Gallistel, 2009; Wagenmakers, 2007; Wetzels et al., 2011). However, it is possible that univariate methods do not capture more subtle differences in patterns of brain activity between bilinguals and monolinguals. Future research using multivariate analyses (i.e., multi-voxel pattern analysis) will be very helpful in addressing this question. Lastly, some have advocated for the use of continuous measure of language experience (such as daily usage and proficiency), cautioning that bilingualism should not be considered as merely a categorical variable (DeLuca, Rothman, Bialystok, & Pliatsikas, 2019; Luk & Bialystok, 2013). Based on this, continuous analyses could be explored in future studies.

While there is prior research to suggest there might be differences in activation between monolinguals and bilinguals during arithmetic because of its link to executive control, we conclude that it is unlikely that the Spanish-English bilingual experience impacts the brain bases of arithmetic. Our findings are important when considering the larger literature on the brain bases of arithmetic processing, where language background of the participants is often not specified, and for future studies, where investigators need not be concerned that bilingual experience represents grounds for exclusion of a participant from a functional neuroimaging study.

4.4 | Implications for education

Early comparisons of monolinguals and bilinguals in the domain of arithmetic arose out of concern that experience with two languages would be detrimental to learners (e.g., Macnamara, 1966), though subsequent research largely suggested that this was not the case for simple arithmetic or for bilinguals with strong proficiency in both of their languages (Geary et al., 1993; Mägiste, 1980; McClain & Huang, 1982). While some studies have found evidence of an advantage on math tasks in bilinguals compared to monolinguals (Daubert & Ramani, 2019; Hartanto et al., 2018), these advantages were restricted to very young children. Our neuroimaging findings inform the existing literature by suggesting that early exposure to two languages (and mastery of these languages) does not affect the neural bases underlying the academically important cognitive skill of arithmetic. In the face of concerns that students may suffer in this domain based on their bilingualism, our results offer evidence to the contrary. Our study also provides a foundation by which to study adults and children with math disability (MD, also termed dyscalculia). Knowing that monolingual and early bilingual groups do not differ in terms of brain activation for simple arithmetic raises the possibility that bilinguals with MD are similar to monolinguals with MD, and therefore have the same functional anomalies relative to their non-MD peers.

5 | CONCLUSION

Here, we addressed the question whether the neural bases of arithmetic differ between monolinguals and bilinguals. Bilinguals can solve

arithmetic problems in either of their two languages. Also, it is possible that the bilingual experience affects skills that support arithmetic (executive function and phonological processing). Prior brain imaging studies of arithmetic have not addressed this possibility and most studies do not even characterize their participants' language experiences. In this study, we addressed this question for the first time and found no difference in brain activity underlying arithmetic when comparing Spanish-English bilinguals with English monolinguals in the context of operation type (subtraction and addition) and age (adults and children). This finding suggests that the neural bases of simple arithmetic are not altered by early bilingual experience. It indicates that the inclusion of Spanish-English early bilingual participants in studies of arithmetic should not alter results, and that results from neuroimaging studies of arithmetic in monolinguals or early bilinguals can likely be generalized to the other group.

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CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or commercial considerations and that this material has not been published (nor is it under consideration for publication) elsewhere.

DATA AVAILABILITY STATEMENT

Data used in this study are available from the corresponding author upon reasonable request.

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