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# Cortical Thickness in bilingual and monolingual children: Relationships to language use and language skill

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## Abstract

There is a growing body of evidence based on adult neuroimaging that suggests that the brain adapts to bilingual experiences to support language proficiency. The Adolescent Brain Cognitive Development (ABCD) Study is a useful source of data for evaluating this claim during childhood, as it involves data from a large sample of American children. Using the baseline ABCD Study data collected at ages nine and ten, the goal of this study was to identify differences in cortical thickness between bilinguals and monolinguals and to evaluate how variability in English vocabulary and English use within bilinguals might explain these group differences. We identified bilingual participants as children who spoke a non-English language and were exposed to the non-English language at home. We then identified a matched sample of English monolingual participants based on age, sex, pubertal status, parent education, household income, non-verbal IQ, and handedness. Bilinguals had thinner cortex than monolinguals in widespread cortical regions. Within bilinguals, more English use was associated with greater frontal and parietal cortical thickness; greater English vocabulary was associated with greater frontal and temporal cortical thickness. These findings replicate and extend previous research with bilingual children and highlight unexplained cortical thickness differences between bilinguals and monolinguals.

### Keywords

Bilingual; MRI; Cortical Thickness; Child

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Code availability statement

Analysis scripts for this study are available on the Open Science Framework (doi: 10.17605/OSF.IO/95QJ8).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit authorship contribution statement

**Kelly A. Vaughn:** Conceptualization, Data curation, Software, Formal analysis, Writing – original draft, Visualization. **My V.H. Nguyen:** Software, Validation, Writing – review & editing. **Juliana Ronderos:** Validation, Writing – review & editing. **Arturo E. Hernandez:** Writing – review & editing, Supervision, Funding acquisition.

Supplementary materials

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## 1. Introduction

Although bilingualism (or multilingualism) is the norm for many cultures around the world, much of the early research on how the brain supports language development during childhood has been focused on monolingual children. A growing body of research has compared the structure and function of the brains of bilingual and monolingual adults, with theories converging on the idea that the brain adapts to bilingual experiences in order to support proficiency in each language (Green & Abutalebi, 2013; Hernandez et al., 2018; Pliatsikas, 2020; Pliatsikas et al., 2020; Stocco et al., 2014). Still, there is limited research focused on how brain structure is related to bilingual skills and experiences during childhood.

Cortical thickness is a key measure of brain structure in relation to bilingual language proficiency during childhood. Multiple studies have connected increased cortical thickness to higher levels of skill development and experience (Burgaleta et al., 2014; Hervais-Adelman et al., 2017; Wei et al., 2011). The Dynamic Restructuring Model (Pliatsikas, 2020) suggests that when someone begins learning a second language, neural changes are seen first in cortical structures, then in subcortical structures, and finally in white matter tracts. Typical brain development patterns involve cortical thinning throughout childhood and adolescence. Therefore, during childhood, thinner cortex may indicate a more mature brain structure, while thicker cortex may reflect skill development (Burgaleta et al., 2014).

A recent cross-sectional analysis of brain development patterns for bilingual and monolingual children (ages 3–21) (Pliatsikas et al., 2020) supports this interpretation of cortical thickness differences. This study found that early in life, bilinguals had thinner cortex than monolinguals, but in adolescence and adulthood, the pattern changed, such that bilinguals had thicker cortex, particularly in frontal and parietal regions, than age-matched monolinguals. The researchers interpreted these findings as delayed cortical thinning for bilingual adolescents.

Within bilinguals, there is some evidence for a relationship between cortical thickness and language skills during childhood. In a sample of children ages 6–13, Archila-Suerte et al. (2018) observed that Spanish-English sequential bilinguals with higher English skills had thicker cortex in left hemisphere language-related regions (e.g., superior temporal gyrus, inferior frontal gyrus, and middle frontal gyrus) than a matched sample of Spanish-English sequential bilinguals with lower English skills. In line with the Dynamic Restructuring Model (Pliatsikas, 2020) and previous research on skill development (Hervais-Adelman et al., 2017; Maguire et al., 2000; Wei et al., 2011; Wenger et al., 2017), these results suggest that increasing second language proficiency during childhood is related to expansion of cortical structures.

To date, no studies have attempted to relate language *use* in bilingual children to specific patterns of cortical thickness. Neuroimaging research with adults has led to theories such as the Adaptive Control Hypothesis (Abutalebi and Green, 2007; Green and Abutalebi, 2013), which suggests that language use patterns are related to a network of frontal and parietal regions (e.g., anterior cingulate cortex, inferior parietal lobule, middle frontal gyrus, and

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superior frontal gyrus). These same regions may be related to language use patterns for bilingual children.

The ABCD Study (Auchter et al., 2018; Barch et al., 2018; Casey et al., 2018; Ewing et al., 2018; Ewing et al., 2018; Garavan et al., 2018; Luciana et al., 2018; Volkow et al., 2018; Zucker et al., 2018) is a useful source of data for investigating the relationship between bilingualism and cortical thickness, as it involves the collection of neural and cognitive data from a large sample of American children throughout adolescence. The goal of this study was to identify differences in cortical thickness for bilinguals and monolinguals and to evaluate how English vocabulary and English use patterns might explain these neural differences. Participants were identified as bilingual or monolingual based on parent demographic questionnaires collected at the one-year follow-up session. Data on English vocabulary, English use, and brain structure were obtained from these participants during the baseline ABCD session, when the participants were nine or ten years old.

## 2. Method

The secondary data analyzes described in this paper were reviewed and approved by Institutional Review Boards at the University of Texas Health Science Center at Houston and the University of Houston. Informed parent consent and child assent was obtained from participants by the ABCD study research team (Garavan et al., 2018). Data included in the secondary analyzes described in this paper was de-identified and obtained from the NIMH Data Archive under ABCD study data release version 3.0 (doi: 10.15154/1519007).

### 2.1. Participants

The sample included in this study is a subset of participants from the ABCD study. The ABCD study contains longitudinal data from over 11,500 children beginning at ages 9–10. Data was collected at 21 sites across the U.S., and children were recruited based on probability sampling of schools near the 21 study sites (Garavan et al., 2018). Recruitment was monitored by the study team to ensure that target demographics were being met such that the resulting sample would be representative of children from diverse backgrounds across the U.S. (Garavan et al., 2018). Participation involves annual in-person visits lasting 6–7 h for children in which they complete interviews, paper-and-pencil questionnaires, iPad tasks, MRI scanning, and in which they provide biospecimens for genetic and hormonal analyzes (not included as part of the current study). At each of these annual visits, parents also complete iPad tasks and interviews. In addition, parents and children complete phone interviews every 3–6 months. Data collection for the ABCD study is ongoing, but the current study used the data from the data release version 3.0, which was collected between 9/1/2016 and 2/15/2020.

Bilingual and monolingual children were selected for the current study from the ABCD study sample (see Fig. 1). We first reduced the sample to those with complete, quality-controlled, and protocol-compliant T1-weighted, T2-weighted, and diffusion MRI data without clinical MRI findings (e.g., hydrocephalus, herniation). We then excluded participants who were missing data from the Parent Longitudinal Demographic Questionnaire (collected during the one-year follow-up visit). From this questionnaire, we

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identified bilinguals as those whose parents reported that either: (a) the child's native language was not English; or (b) the child's native language was English, but English is used equal to or less than another language in the home. Monolinguals were identified as those whose parents reported that the child's native language was English, English was used more than any other language at home, and the child had never been enrolled in a dual language program at school. We then removed children whose self-reported language knowledge conflicted with their grouping (i.e., children in the "bilingual" group who reported that they did not speak a language other than English and children in the "monolingual" group who reported that they did speak a language other than English). This resulted in a much larger sample of monolingual children compared to bilingual children, so we used propensity score matching (Randolph and Falbe, 2014) to select a sample of monolingual children that matched the sample of bilingual children in terms of age, sex, pubertal status (measured via parent-report of the changes in height, body hair, acne, voice deepening, menstruation, etc., compared to other same-aged children), household income, non-verbal IQ (measured via the matrix reasoning subtest of the Weschler Intelligence Scale for Children – Fifth Edition; (Wechsler, 2014)), and handedness (measured via the Edinburgh Handedness Inventory; (Oldfield, 1971)). Any children with missing data for these matching variables were removed from the sample. The questionnaire, task-based, and MRI-based data described below was obtained from every child in this sample. The resulting sample and corresponding data is available on the NIMH data archive under study doi:10.15154/1521158.

## 2.2. Measures

### 2.2.1. Questionnaires

**2.2.1.1. Parent longitudinal demographic questionnaire.:** Parents completed a demographic questionnaire at the baseline session and at the one-year follow-up session. The demographic questionnaire was modified from the PhenX toolkit (Hamilton et al., 2011). The key items from the questionnaire for the current study were questions about the child's native language (i.e., "What is your child's native language?"); the home language environment (i.e., The child's parents or guardians spoke in English more than any other language after birth; English and another language were spoken equally; The child's parents or guardians spoke a language other than English more than any other language after birth); whether the child ever attended a dual language program at school; parent race and ethnicity; parent education; and household income. Questions about the child's native language and home language environment were added after the baseline session, so the current study used data from this survey collected at the one-year follow-up session. All other data described below was obtained at the baseline session.

**2.2.1.2. Edinburgh Handedness Inventory.:** Participants completed a brief version of the Edinburgh Handedness Inventory (Oldfield, 1971; Veale, 2014) that contained four items: writing, throwing, using a spoon, and using a toothbrush, rated on a five-point scale from always right hand to always left hand. Based on their responses, participants were identified as right-handed, left-handed, or ambidextrous. See Luciana et al. (2018) for a complete description.

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**2.2.1.3. Language use (Youth Acculturation Survey).:** This measure was a subset of questions from the PhenX Acculturation protocol (Hamilton et al., 2011). Participants were asked how well they speak English (i.e., poor, fair, good, excellent) and if they speak or understand another language besides English. If they speak or understand a language other than English, they were then asked to identify the other language and to rate their language use with family and their language use with friends on a 5-point scale (1 = Other language all of the time; 5 = English all of the time). See Zucker et al. (2018) for more information.

**2.2.1.4. Pubertal development scale.:** Children reported their pubertal status using the Pubertal Development Scale (Barch et al., 2018; Petersen et al., 1988). This questionnaire asks about body hair, skin change (e.g., acne), growth spurt, voice change (males only), facial hair (males only), breast change (females only), and menarche (females only). Children respond to each item on a 4-point scale where 1 = no development; 2 = beginning development; 3 = additional development; and 4 = development already past (menarche coded dichotomously as 1 = premenarcheal; 4 = postmenarcheal). For each child, we used the summary scores across each domain as a measure of pubertal status ranging from 1 (no development in any domain) to 4 (development already past in all domains). Pubertal status, along with age and sex, was included as a covariate in all analyzes and used to match monolingual participants to the sample of bilingual participants.

### 2.2.2. Behavioral tasks

**2.2.2.1. English picture vocabulary.:** English receptive picture vocabulary was measured using the NIH Toolbox Picture Vocabulary Task (Gershon et al., 2013). This is an iPad task in which participants see four pictures and are asked to touch the picture that matches the word they hear presented from an audio recording. The task is adaptive to ensure appropriate difficulty for each child. For the current study, we age-corrected scores, provided by the ABCD research team (mean = 100; SD = 15). See Luciana et al. (2018) for more information.

**2.2.2.2. Matrix reasoning.:** Non-verbal IQ was measured using an automated version of the Matrix Reasoning subtest from the Wechsler Intelligence Test for Children-V (WISC-V) (Wechsler, 2014). Participants see an array of visuospatial stimuli with a missing item on an iPad. They must select one of four options to complete the array. There are 32 trials, and testing stops if the participant misses three items in a row. Normative standard scores have a mean of 10 and a standard deviation of 3. See Luciana et al. (2018) for more information.

**2.2.3. Neuroimaging—**Neuroimaging data was collected at 21 different ABCD study sites on 3T MRI scanners (Siemens Prisma, General Electric (GE) 750 and Philips) using standard adult-size head coils. MRI data was collected in a fixed order, which included (1) a 3D T1-weighted image; (2) a resting-state functional MRI (fMRI) scan; (3) diffusion tensor imaging (DTI); (4) a 3D T2-weighted image; (5) another resting-state fMRI scan; and (6) three task-based fMRI scans. Children watched a movie during the T1-weighted, T2-weigthed and DTI scans. See Casey et al. (2018) for a complete description of the MRI scanning protocols and parameters.

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**2.2.3.1. Preprocessing.:** All data was analyzed using a collection of processing steps from the Multi-Modal Processing Stream at the University of California, San Diego (Hagler et al., 2019). Preprocessing involved distortion and motion correction and between-modality (i.e., T1-weighted; T2-weighted, DTI, fMRI) registration. The details of these preprocessing steps are described elsewhere (Hagler et al., 2019).

**2.2.3.2. Cortical thickness.:** To extract cortical thickness measures, the preprocessed T1-weighted and T2-weighted (i.e., structural) MRI data was processed in FreeSurfer v5.3.0 (Fischl, 2012) (http://surfer.nmr.mgh.harvard.edu). As described in Hagler et al. (2019), image preprocessing involved correcting for gradient non-linearilty distortions (Jovicich et al., 2006), registering the T2-weighted images to the T1-weighted images using mutual information (Wells et al., 1996), correcting intensity non-uniformity based on tissue segmentation and sparse spatial smoothing, and resampling with 1mm isotropic voxels into rigid alignment with an atlas brain. Then, cortical reconstruction was performed using the standard FreeSurfer pipeline (i.e., skull-stripping Ségonne et al. 2004), white matter segmentation (Dale et al., 1999), correcting topological defects (Fischl et al., 2001; Ségonne et al., 2007), surface optimization (Dale et al., 1999; Dale and Sereno, 1993; Fischl and Dale, 2000), and non-linear registration to a surface-based atlas (Fischl et al., 1999). FreeSurfer initial intensity scaling and N3 intensity inhomogeneity correction were not included, as these corrections were applied during image preprocessing. Cortical surfaces reconstructed in FreeSurfer were registered to the Desikan atlas (Desikan et al., 2006), and average cortical thickness within each parcellation in the atlas was calculated using fuzzy-cluster parcellations (Chen et al., 2012). See Halger and colleagues (2019) for a full description of the processing pipeline.

It is important to highlight that we extracted the data from FreeSurfer and conducted our analyzes on the average cortical thickness in each region from the Desikan atlas rather than a vertex-by-vertex whole-brain analysis of cortical thickness within FreeSurfer. This approach allowed us to use the FreeSurfer output that the ABCD study team preprocessed, compiled, and released, rather than independently processing the data in FreeSurfer. Using the preprocessed data released by the ABCD study team ensures consistency with other studies using the ABCD data.

Because the data for the ABCD study was collected across different study sites around the U.S., we included additional preprocessing steps to harmonize the cortical thickness results across scanners. We used the neuroCombat R package (https://github.com/Jfortin1/neuroCombat_Rpackage; (Fortin et al., 2018) to generate harmonized values of cortical thickness across each region based on the scanner model used to collect the data. The ABCD data included in this study was collected on five different scanner models: Siemens Prisma ($n = 400$); Siemens Prisma Fit ($n = 392$); GE Discovery MR750 ($n = 369$); Phillips Achieva dStream ($n = 116$), and Phillips Ingenia ($n = 53$). For 26 subjects, no scanner model information was available, so we entered these subjects into the harmonization as “unknown.” A Chi-squared test indicated no significant differences in scanner model across bilinguals and monolinguals ($\chi^2$ (5) = 4. 08; $p$ = 0. 54). The results presented are based on the harmonized cortical thickness data.

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### 2.3. Analyzes

In order to conduct the analyzes described below, we created custom code in RStudio version 1.3.1056. We used this custom code for (1) subject selection; (2) extracting language variables from the ABCD dataset; (3) extracting cortical thickness variables from the ABCD dataset; (4) evaluating demographic data; (5) running the ANCOVA to compare cortical thickness between bilinguals and monolinguals; and (6) running the multiple regression to understand the unique relationships between English use, English vocabulary, and cortical thickness within bilinguals. All of these scripts are available on the Open Science Framework (doi:10.17605/OSF.IO/95QJ8). The data from subjects included in the analyzes is available on the NIMH Data Archive (doi:10.15154/1521158)

The ANCOVAs and regressions described below assume that cortical thickness in each region is normally distributed. Across all of the brain regions examined, the skewness of cortical thickness ranged from −0.78 to 0.53 and the kurtosis of cortical thickness ranged from −0.21 to 1.74. Following (Kim, 2013), these values fall within an acceptable range to meet the assumption of normality (i.e., with sample sizes > 300, skewness between −2 and 2 and kurtosis between −7 and 7). See Supplemental Table 1 for skewness and kurtosis values for cortical thickness in each brain region.

**2.3.1. Cortical thickness differences between bilinguals and monolinguals—** As described above, bilingual participants ($n = 678$) were selected from the ABCD study based on their parent- and self-reported experience with and knowledge of a language other than English. A monolingual comparison group ($n = 678$) was selected based on propensity score matching (Randolph and Falbe, 2014) to the bilingual group on: age, sex, pubertal status, household income, and non-verbal IQ. To compare the bilingual and monolingual groups on cortical thickness, we conducted one-way, two-sided, between-groups ANCOVAs in which we examined bilingual/monolingual differences while controlling for the matching variables described above (i.e., age, sex, pubertal status, household income, parent education, non-verbal IQ, and handedness). After conducting the ANCOVAs for each region, we computed False Detection Rate (FDR) corrections (Benjamini and Hochberg, 1995) for all of the analyzes. We only report the results that were significant at an FDR-corrected alpha of 0.05.

**2.3.2. English use, english vocabulary and cortical thickness for bilinguals—** Next, we evaluated whether variability within bilinguals ($n = 678$) in English vocabulary and English use with family and friends was related to cortical thickness. As described above, in the Youth Acculturation Survey, bilingual participants self-reported their use of English and another language with their friends and with their family on a scale of 1–5 where 5 indicates only English is used and 1 indicates only another language is used. Similar to Dick et al. (2019) approach to calculate “bilingual use” from this measure, we converted the 1–5 scale to a 0–4 scale where 0 = Other language all of the time and 4 = English all of the time. Then, we summed the ratings for language use with family and language use with friends to develop a 0–8 score. Unlike Dick et al. (2019), we did not reverse score the language use variable, so in the current study 0 = Only other language with family & friends and 8 = Only

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English with family & friends. Scores in the middle of this range represent more balanced language use.

We conducted two-sided multiple regression analyzes focused on language use with friends and family and English vocabulary (assessed via the NIH toolbox), controlling for age, sex, pubertal status, household income, parent education, non-verbal IQ, and handedness. As described above, we applied FDR-corrections to each analysis and report only the results that were significant at an FDR-corrected alpha of 0.05.

## 3. Results

### 3.1. Demographics

See Table 1 for a comparison of demographic and matching variables for bilinguals and monolinguals. After matching, bilinguals and monolinguals did not differ significantly in age, sex, pubertal status, non-verbal IQ, household income, parent education, handedness, or parent identity (i.e., mom/dad). More bilingual children identified as Hispanic/Latino than monolingual children; bilingual and monolingual children differed in their native language and their parent's native language. Bilinguals had significantly lower English vocabulary than monolinguals, but the mean vocabulary scores of both bilingual and monolingual children were greater than the standardized mean of 100. Bilingual children, on average, reported balanced use of English and their other language with family and friends. Bilingual children who reported using more English with family also reported using more English with friends ($r = 0.25$, $p < 0.001$). Bilingual children who reported using more English with both family and friends had higher English vocabulary scores ($r = 0.27$, $p < 0.001$).

### 3.2. Cortical thickness differences between bilinguals and monolinguals

When controlling for age, sex, pubertal status, non-verbal IQ, household income, parent education, and handedness, bilinguals had thinner cortex than monolinguals in many bilateral brain regions (for all significant results: $F(1,1347)$'s > 5.19; FDR-corrected $p$'s < 0.05, partial $\eta^2 \geq 0.003$; see Fig. 2 and Table 3). Bilinguals also had thicker cortex than monolinguals in the right medial orbitofrontal gyrus ($F(1,1347) = 5.585$; FDR-corrected $p = 0.018$, partial $\eta^2 = 0.004$). See Supplemental Table 2 for full ANCOVA results including test statistics, FDR-corrected p-values, and effect sizes for all covariates.

### 3.3. Bilingual english use, english vocabulary and cortical thickness

Within bilinguals, using more English, relative to their other language, with family and friends was related to thicker cortex in the bilateral inferior parietal lobules; left caudal anterior cingulate cortex, superior frontal gyrus, and superior parietal lobule; and right precentral gyrus and parahippocampal gyrus (all significant FDR-corrected $p$'s < 0.05, $\beta$'s ≥ 0.012, see Fig. 3). Conversely, higher English vocabulary within bilinguals was related to thicker cortex in the bilateral superior temporal gyri; left caudal and rostral middle frontal gyrus, pars-opercularis (part of the inferior frontal gyrus), and precentral gyrus; and right inferior temporal gyrus, middle temporal gyrus, and supramarginal gyrus; with the largest effect size observed in the right superior temporal gyrus (all significant FDR-corrected $p$'s <

0.05, $\beta$'s ≥ 0.005, see Fig. 4). See Supplemental Table 3 for full regression results including betas, standard error, FDR-corrected p-values, and effect sizes for all covariates.

## 4. Discussion

The goal of this study was to identify differences in cortical thickness between bilinguals and monolinguals and to evaluate how English vocabulary and English use patterns might explain these neural differences. Cortical thickness is a measure of the linear distance between the pial surface and the white matter surface. It increases in the first few years of life, and then steadily declines from around age five or six through adulthood (Ducharme et al., 2016; Lyall et al., 2015), which may reflect decreases in gray matter driven by cell death or synaptic pruning, or may be driven by increases in white matter (Natu et al., 2019; Wenger et al., 2017). This steady decline throughout childhood, adolescence, and adulthood makes cortical thickness data fairly easy to interpret in terms of brain development, where thinner cortex might indicate more mature brain development, and thicker cortex may reflect extended neuroplasticity. For example, Burgaleta et al. (2014) found that children with stable IQ scores showed typical cortical thinning over time, whereas children who did not display cortical thinning had increases in IQ scores over time. Within the bilingualism literature, Pliatsikas et al. (2020) interpreted thicker cortex for bilingual adolescents compared to monolingual adolescents as delayed cortical thinning.

In the current study, we identified widespread cortical thickness differences between bilinguals and monolinguals after matching the samples on age, sex, pubertal status, household income, parent education, non-verbal IQ, and handedness and including each of these variables as covariates in our analyzes. In many existing neuroimaging studies, the inability to match samples or control for some of these covariates has raised concerns that differences in brain structure between bilinguals and monolinguals actually reflect socioeconomic status differences. Results of the current study highlight that even after matching and controlling for socioeconomic status, widespread differences between bilinguals and monolinguals were observed. Some of these group differences were related to bilingual English vocabulary skills, and others were related to bilingual patterns of English use. Still, some cortical thickness differences between bilinguals and monolinguals were unrelated to bilingual English vocabulary and English use (e.g., visual regions, precuneus, posterior cingulate cortex, etc.). Considering which of the group differences were related to English vocabulary and English use can aid in developing and testing theories about bilingual neurocognition during childhood.

The results of our bilingual/monolingual comparisons replicate previous findings with pre-adolescent children (Pliatsikas et al., 2020). Specifically, bilingual children at ages nine to ten had thinner cortex than monolingual children. We also replicated the findings by Archila-Suerte et al. (2018) – bilingual children with higher English vocabulary skills had thicker cortex in frontal and temporal regions within the language network (Friederici and Gierhan, 2013). Importantly, the current study replicated these findings using a much larger sample of children (i.e., $n$ = 678 bilinguals and $n$ = 678 monolinguals) within a restricted age range (i.e., nine-ten years old). Recent research has highlighted the importance of large samples for detecting true differences between bilinguals and monolinguals (Munson and



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Hernandez, 2019). Our ability to replicate previous findings from Plistsikas et al. (2020) and Archila-Suerte et al. (2018) using a large sample of children strengthens the conclusions those authors made about their findings.

In previous research (Pliatsikas et al., 2020), bilingual adolescents had thicker cortex than monolinguals in frontal and parietal regions. In the current study, we found that bilingual children who used more English, relative to their other language, with their family and friends had thicker cortex in frontal and parietal regions. These regions align well with the network of brain areas involved in language control and cognitive control, as outlined by Abutalebi and Green (2007), and later incorporated into the Adaptive Control Hypothesis (Green and Abutalebi, 2013) – specifically the anterior cingulate cortex, inferior parietal lobule, and superior frontal gyrus. This is some of the first evidence to indicate that these brain regions are associated with language use for bilinguals in childhood.

It is important to note that the regions in which more bilingual English use or higher bilingual English vocabulary were associated with thicker cortex were also some of the regions in which bilinguals as a group had thinner cortex than monolinguals. In other words, higher English use and vocabulary for bilinguals was associated with more “monolingual-like” cortical thickness in language-related brain regions and control-related brain regions. This is in line with claims that bilingualism is a continuum, rather than a categorically different language experience from monolingualism (DeLuca et al., 2019; Luk and Bialystok, 2013; Pliatsikas et al., 2020). When bilingual children in this sample used and understood more English, their brains appeared more similar to the English monolingual children.

### 4.1. Limitations and future directions

The ABCD study allows for a large-scale comparison of bilingual and monolingual children, but since it was not designed to study bilingualism, the data collected about bilingual language skills and language use were limited. Although both an English and a Spanish version of the NIH toolbox are available, the ABCD study only includes the English version (Luciana et al., 2018). Assessing language skills in both the first and second languages would allow us to identify whether weaker English skills are a result of general language abilities or if participants are more proficient in their native languages. In addition, the ABCD study excluded individuals who were not proficient in English. Therefore, our results may reflect the higher end of English skills for bilingual children.

Using the available language use data from the ABCD study, we were able to create a continuum from mostly Spanish with family and friends to mostly English with family and friends. Children with more balanced use of both languages fell somewhere in the middle of this continuum. Notably, balanced language use on this measure could suggest that a child uses English with some friends or family members and Spanish with other friends or family members or that the child often mixes English and Spanish. These two language use patterns cannot be distinguished based on the available language use information. This is an important distinction to be made in future research, as the Adaptive Control Hypothesis (Green and Abutalebi, 2013) suggests that neural outcomes would be different for children

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who mix English and Spanish often when communicating with friends and family compared with children who use each language in separate contexts.

In addition to a more comprehensive measure of language use, it would be helpful to consider age of English acquisition in these analyzes. Bilingual children in this study were those whose parents reported that their native language was not English or that a language other than English was spoken in their home at least half of the time. Therefore, some of the bilingual children may have heard some English in the home, while other bilingual children may not have been exposed to English until ages 4–6, when they entered school. Research suggest that the age at which a second language was acquired impacts brain structure (Claussenius-Kalman et al., 2020; Klein et al., 2014). Specifically, theories such as the sensorimotor hypothesis (Hernandez and Li, 2007) suggest that when a language is learned in infancy, it builds from low-level sensory information to complex speech in the same way that any native language develops. Languages learned later in life may instead build off of existing knowledge of the native language (e.g., cognates, grammatical structures, etc.). In the brain, languages learned very early might be related to earlier-developing brain regions such as subcortical structures and primary auditory cortex. Languages learned later may instead be related to brain regions involved in higher cognitive functions, such as the frontal lobe. Future studies should explore whether brain structure differences related to age of acquisition of a second language can be observed as early as ages 9–10.

Finally, cortical thickness is not the only way to measure brain structure. Other studies comparing brain structure between bilinguals and monolinguals have examined cortical and/or subcortical volume (Archila-Suerte et al., 2018; Burgaleta et al., 2016; Claussenius-Kalman et al., 2020; Della Rosa et al., 2013; Li et al., 2014; Mechelli et al., 2004; Pliatsikas et al., 2020). Cortical volume can be thought of as the combination of cortical thickness and surface area (Wenger et al., 2017). Surface area reflects both the size of the brain and the amount of gyrification, or folding, of the cortex (i.e., larger brain = larger surface area; more gyrification = larger surface area). While cortical thickness shows a linear decrease throughout late childhood and adolescence, surface area appears to develop non-linearly, with peaks occurring between ages 8–11 (Wierenga et al., 2014). Subcortical volume development seems to depend on the region, with some regions increasing in volume with age and other regions decreasing in volume with age (Giedd et al., 2015; Raznahan et al., 2014). In the context of the current study, surface area, cortical volume, and subcortical volume may be more difficult to interpret than cortical thickness because of their developmental trajectories. Still, future research should explore how bilingualism relates to differences in multiple measures of brain structure across development, as each measure can provide unique information about brain development (Claussenius-Kalman et al., 2020).

### 4.2. Conclusion

Making use of a large sample of bilingual and monolingual children in the U.S., the current study replicated and extended previous research on the neuroanatomy of bilingualism during childhood. Even when bilinguals and monolinguals were matched on age, sex, pubertal status, non-verbal IQ, parent education, household income, and handedness, and when these variables were also included as covariates in analyzes, bilingual children had

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thinner cortex than monolingual children across a widespread network of brain regions. Bilinguals with higher English vocabulary had thicker (more “monolingual-like”) cortex in language-related brain regions, including the bilateral superior temporal gyri and left frontal regions. Bilinguals with greater English use with family and friends, relative to their other language, had thicker (more “monolingual-like”) cortex in regions associated with language- and cognitive-control, including the anterior cingulate cortex, inferior parietal lobule, and superior frontal gyrus. These findings highlight the importance of understanding the neuroanatomy of bilingualism by focusing on variability within bilinguals rather than simply comparing bilinguals and monolinguals. More research is needed to understand how the widespread neural differences between bilinguals and monolinguals are related to specific aspects of the bilingual experience in order to develop robust theories about bilingual neurocognition.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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## Data availability statement

Data included in the secondary analyzes described in this paper was de-identified and obtained from the NIMH Data Archive under ABCD study data release version 3.0 (doi: 10.15154/1519007). The selected sample described in this manuscript and their corresponding data is available on the NIMH data archive under study doi:10.15154/1521158. The data used to generate Figs. 2–4 is available in the main text and supplemental materials associated with this manuscript.

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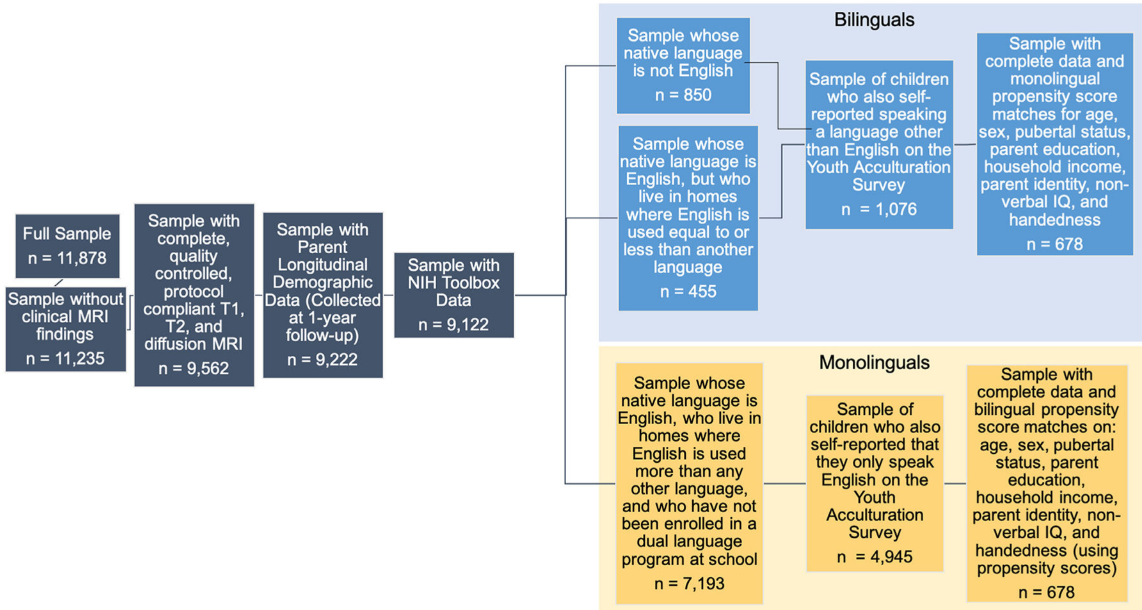


**Fig. 1.**

Pipeline for identifying bilingual and monolingual participants from the ABCD Release 3.0

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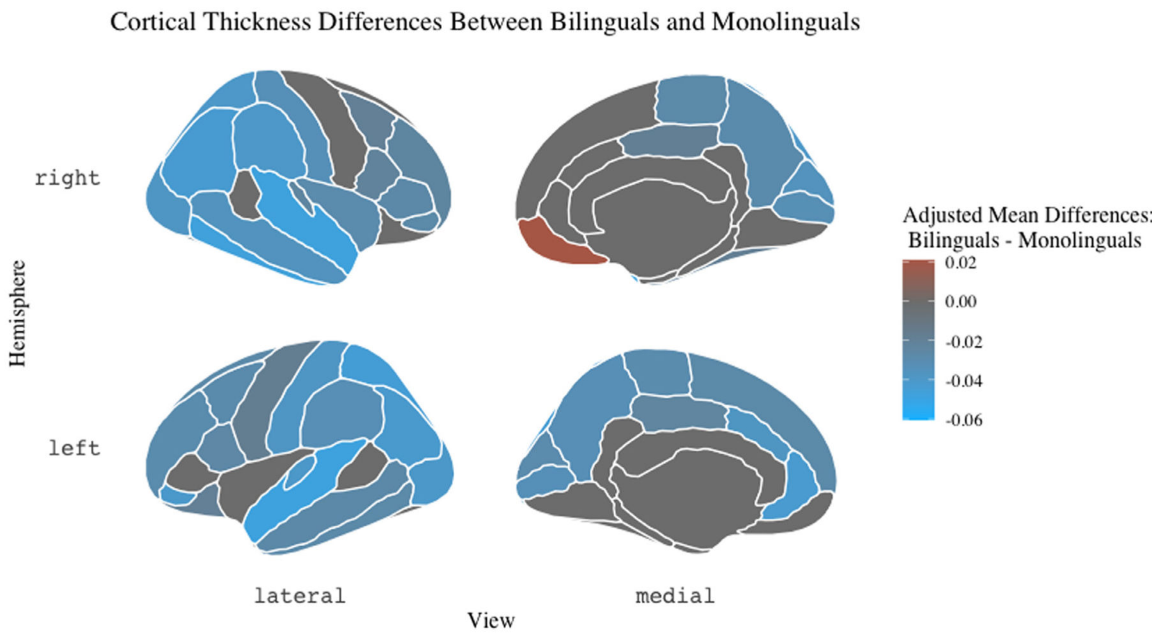


**Fig. 2.**

Significant cortical thickness differences between bilinguals and monolinguals. Fig. 2 Legend. Blue indicates thinner cortex for bilinguals than monolinguals; Red indicates thicker cortex for bilinguals than monolinguals. All results presented were significant after controlling for age, sex, pubertal status, non-verbal IQ, household income, parent education, and handedness. Figure created using the ggseg R package (Mowinckel & Vidal-Piñeiro, 2020).

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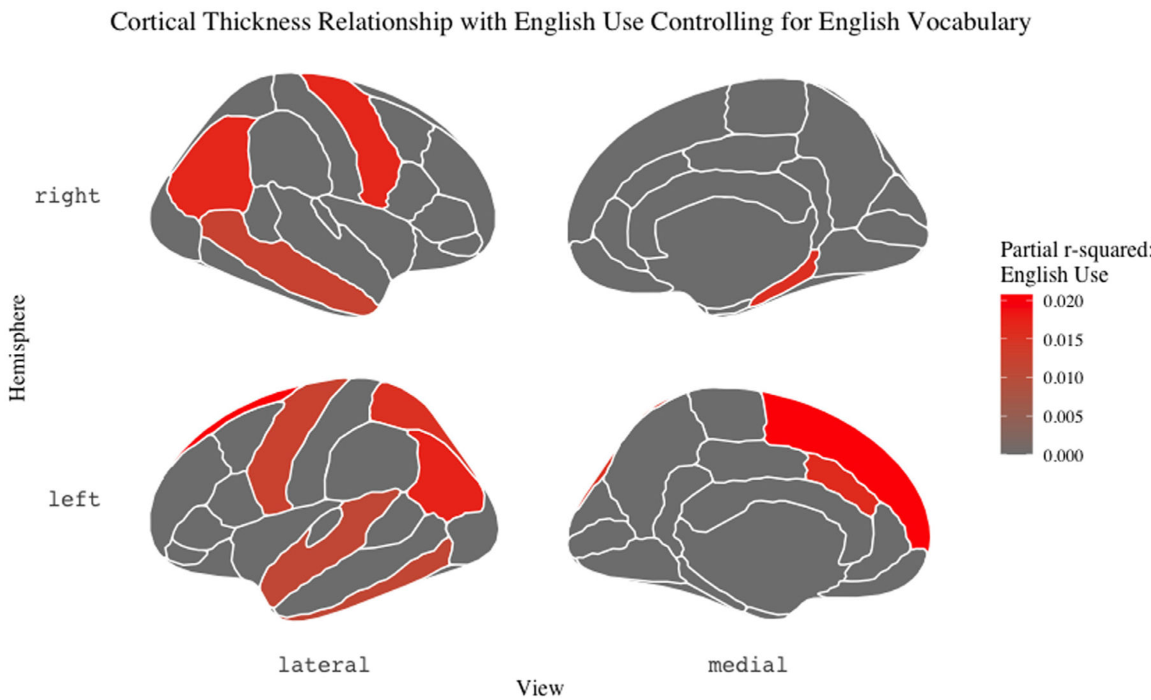


**Fig. 3.**

Significant relationships between English use and cortical thickness within bilinguals. Fig. 3 Legend. Red indicates thicker cortex associated with more English use with family and friends when controlling for English vocabulary, age, sex, pubertal status, non-verbal IQ, household income, parent education, and handedness. Figure created using the ggseg R package (Mowinckel & Vidal-Piñeiro, 2020).

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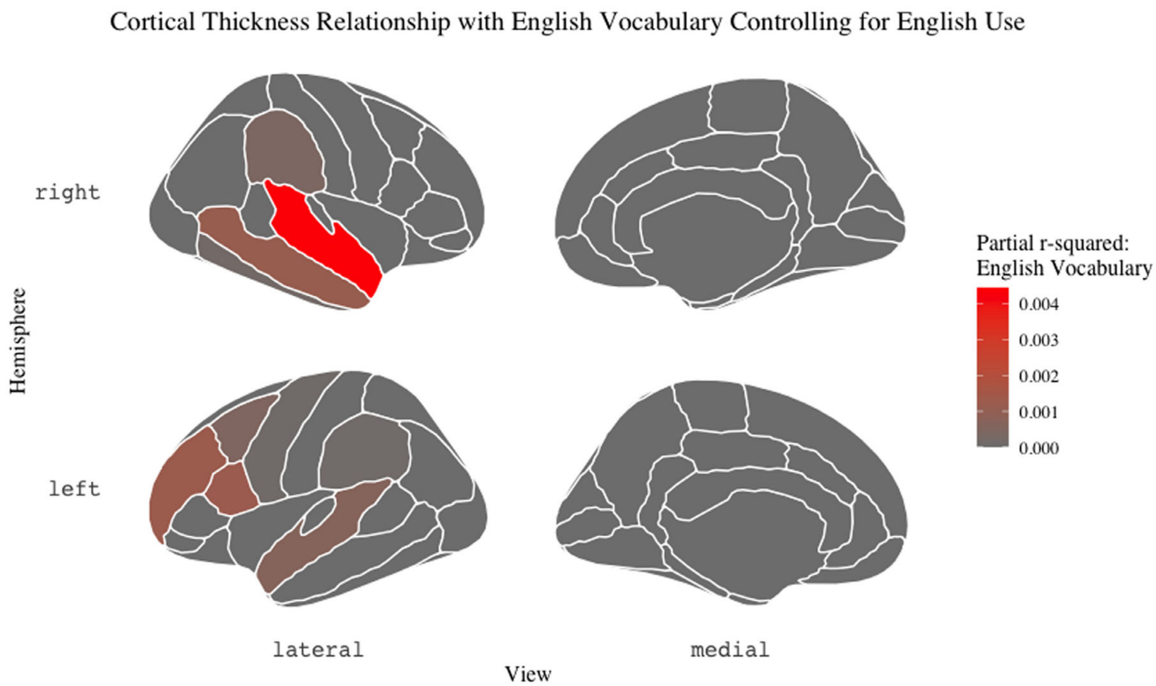


**Fig. 4.**

Significant relationships between English vocabulary and cortical thickness within bilinguals. Fig. 4 Legend. Red indicates thicker cortex associated with higher English vocabulary when controlling for English use with family and friends, age, sex, pubertal status, non-verbal IQ, household income, parent education, and handedness. Figure created using the ggseg R package (Mowinckel & Vidal-Piñeiro, 2020).

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## Table 1

Demographic information for bilinguals and monolinguals.

| | Bilinguals | Monolinguals | Test-Statistic for Comparison | *p*-value |
|---|---|---|---|---|
| Age in months: Mean (SD) | 131.05 (7.55) | 130.63 (7.72) | $t(1354) = 1.02$95% CI: (−0.39, 0.31) | 0.31 |
| Sex (n) | Males: 412<br>Females: 266 | Males: 408<br>Females: 270 | $\chi^2$ (1) = 0.03 | 0.87 |
| Pubertal Status: Mean (SD) | 2.12 (0.84) | 2.13 (0.84) | $t(1354) = -0.29$95% CI: (−0.10, 0.08) | 0.77 |
| Non-Verbal IQ: Mean (SD) | 9.80 (2.95) | 9.70 (2.92) | $t(1354) = 0.61$95% CI: (−0.22, 0.41) | 0.54 |
| Household Income: Mean (SD) | 6.24 (2.49) | 6.21 (2.96) | $t(1315.3) = 0.22$95% CI: (−0.26, 0.32) | 0.83 |
| Parent's Education: Mean (SD) | 15.45 (3.80) | 15.76 (2.70) | $t(1222) = -1.73$95% CI: (−0.66, 0.04) | 0.09 |
| Handedness (n) | Right: 556<br>Left: 43<br>Mixed: 79 | Right: 543<br>Left: 42<br>Mixed: 93 | $\chi^2$ (2) = 1.30 | 0.52 |
| Parent Identity (n) | Dad: 101<br>Mom: 577 | Dad: 108<br>Mom: 570 | $\chi^2$ (2) = 0.20 | 0.65 |
| Ethnicity (n) | Hispanic/Latino: 492<br>Not Hispanic/Latino:178 | Hispanic/Latino: 33<br>Not Hispanic/Latino: 631 | $\chi^2$ (1) = 652.08 | < 0.001 |
| Child's Native Language (n) | English: 222<br>Spanish: 359<br>Other: 97 | English: 678<br>Spanish: 0<br>Other: 0 | $\chi^2$ (2) = 687.04 | < 0.001 |
| Parent's Native Language (n) | English: 85<br>Spanish: 463<br>Other: 130 | English: 657<br>Spanish: 5<br>Other: 16 | $\chi^2$ (2) = 978.18 | < 0.001 |
| English Vocabulary: Mean (SD) | 101.99 (15.74) | 105.63 (17.33) | $t(1341.7) = -4.04$95% CI: (−5.49, −1.87) | < 0.001 |
| English Use with Family and Friends: Mean (SD) | 4.82 (1.67) | N/A | N/A | N/A |

*Note*. CI: Confidence Interval.

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## Table 2

Relationship between English vocabulary and English use with covariates

| | English Vocabulary | | Bilinguals' English Use[a] | |
|---|---|---|---|---|
| | **Test-Statistic** | ***p*-value** | **Test-Statistic** | ***p*-value** |
| Age | $r = 0.03$95% CI: (−0.03, 0.08) | 0.34 | $r = -0.01$95% CI: (−0.08, 0.07) | 0.82 |
| Sex | $t(1354) = -0.67$95% CI: (−2.44, 1.19) | 0.50 | $t(671) = 0.36$95% CI: (−0.21, 0.31) | 0.72 |
| Pubertal Status | $r = -0.12$95% CI: (−0.17, − 0.07) | < 0.001 | $r = -0.05$95% CI: (−0.13, 0.02) | 0.18 |
| Non-Verbal IQ | $r = 0.34$95% CI: (0.29, 0.38) | < 0.001 | $r = 0.17$95% CI: (0.10. 0.24) | < 0.001 |
| Household Income | $r = 0.39$95% CI: (0.35, 0.43) | < 0.001 | $r = 0.35$95% CI: (0.29, 0.42) | < 0.001 |
| Parental Education | $r = 0.36$95% CI: (0.31, 0.41) | < 0.001 | $r = 0.31$95% CI: (0.24, 0.37) | < 0.001 |
| Handedness | $F(2,1353) = 0.68$ | 0.51 | $F(2,670) = 2.53$ | 0.08 |

Table 2 shows the relationship between English vocabulary and English use with the covariates. English vocabulary scores across both bilinguals and monolinguals were significantly related to pubertal status, non-verbal IQ, household income, and parental education. English use within bilinguals was significantly related to non-verbal IQ, household income, and parental education. Except for pubertal status, all of these relationships were positive, such that higher non-verbal IQ, higher household income, and higher parental education were associated with more English use and higher English vocabulary skills. Notably, although the relationships between non-verbal IQ and bilinguals' English use and between pubertal status and English vocabulary were significant, they were weaker than the other relationships. Future research should further explore these relationships.

*Notes.*

[a]Combined use with family and friends. $r$ indicates Pearson's correlation. CI: Confidence Interval.

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### Table 3

Cortical thickness differences between bilinguals and monolinguals after adjusting for covariates.

| Region | $F$(1,1347) | FDR-corrected $p$-value | Partial $\eta^2$ | Monolingual Adjusted Mean [95% CI] | Bilingual Adjusted Mean [95% CI] |
|---|---|---|---|---|---|
| Left Frontal Lobe | | | | | |
| Left Frontal Pole | 12.461 | 0.001 ** | 0.009 | 3.212 [3.188, 3.236] | 3.152 [3.128, 3.175] |
| Left Medial Orbitofrontal Gyrus | 1.381 | 0.282 | 0.001 | 2.731 [2.718, 2.744] | 2.742 [2.729, 2.754] |
| Left Lateral Orbitofrontal Gyrus | 6.038 | 0.022 * | 0.004 | 2.986 [2.975, 2.997] | 2.967 [2.956, 2.978] |
| Left Pars Opercularis | 10.628 | 0.003 ** | 0.008 | 2.913 [2.902, 2.924] | 2.887 [2.876, 2.898] |
| Left Pars Orbitalis | 14.083 | 0.001 ** | 0.010 | 3.137 [3.122, 3.152] | 3.096 [3.081, 3.111] |
| Left Pars Triangularis | 2.832 | 0.119 | 0.002 | 2.818 [2.806, 2.829] | 2.804 [2.792, 2.815] |
| Left Rostral Middle Frontal Gyrus | 12.805 | 0.001 ** | 0.009 | 2.730 [2.718, 2.741] | 2.700 [2.689, 2.712] |
| Left Caudal Middle Frontal Gyrus | 13.148 | 0.001 ** | 0.010 | 2.878 [2.867, 2.889] | 2.849 [2.838, 2.860] |
| Left Superior Frontal Gyrus | 11.167 | 0.002 ** | 0.008 | 3.135 [3.124, 3.147] | 3.108 [3.124, 3.147] |
| Left Rostral Anterior Cingulate Cortex | 13.518 | 0.001 ** | 0.010 | 3.169 [3.153, 3.185] | 3.126 [3.110, 3.142] |
| Left Caudal Anterior Cingulate Cortex | 8.949 | 0.005 ** | 0.007 | 2.885 [2.867, 2.902] | 2.846 [2.867, 2.902] |
| Left Precentral Gyrus | 4.838 | 0.041 * | 0.004 | 2.790 [2.779, 2.801] | 2.773 [2.762, 2.784] |
| Left Insula | 0.458 | 0.538 | 0.000 | 3.298 [3.288, 3.309] | 3.293 [3.283, 3.304] |
| Right Frontal Lobe | | | | | |
| Right Frontal Pole | 3.722 | 0.073 | 0.003 | 3.176 [3.153, 3.199] | 3.143 [3.120, 3.167] |
| Right Medial Orbitofrontal Gyrus | 5.316 | 0.031 * | 0.004 | 2.738 [2.726, 2.751] | 2.759 [2.747, 2.772] |
| Right Lateral Orbitofrontal Gyrus | 0.303 | 0.619 | 0.000 | 2.958 [2.947, 2.970] | 2.954 [2.943, 2.965] |
| Right Pars Opercularis | 8.023 | 0.009 ** | 0.006 | 2.905 [2.895, 2.916] | 2.883 [2.872, 2.894] |
| Right Pars Orbitalis | 6.344 | 0.020 * | 0.005 | 3.109 [3.094, 3.125] | 3.082 [3.066, 3.097] |
| Right Pars Triangularis | 9.832 | 0.004 ** | 0.007 | 2.806 [2.794, 2.818] | 2.779 [2.766, 2.791] |
| Right Rostral Middle Frontal Gyrus | 9.403 | 0.004 ** | 0.007 | 2.690 [2.679, 2.701] | 2.666 [2.655, 2.677] |
| Right Caudal Middle Frontal Gyrus | 6.086 | 0.022 * | 0.004 | 2.845 [2.834, 2.856] | 2.826 [2.815, 2.837] |
| Right Superior Frontal Gyrus | 1.733 | 0.229 | 0.001 | 3.095 [3.084, 3.106] | 3.085 [3.074, 3.096] |
| Right Rostral Anterior Cingulate Cortex | 0.467 | 0.538 | 0.000 | 3.055 [3.039, 3.072] | 3.063 [3.047, 3.080] |
| Right Caudal Anterior Cingulate Cortex | 0.020 | 0.889 | 0.000 | 2.747 [2.731, 2.762] | 2.745 [2.729, 2.761] |

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| Region | $F(1,1347)$ | FDR-corrected $p$-value | Partial $\eta^2$ | Monolingual Adjusted Mean [95% CI] | Bilingual Adjusted Mean [95% CI] |
|---|---|---|---|---|---|
| Right Precentral Gyrus | 4.141 | 0.060 * | 0.003 | 2.755 [2.745, 2.766] | 2.740 [2.729, 2.750] |
| Right Insula | 12.868 | 0.001 ** | 0.009 | 3.300 [3.289, 3.312] | 3.272 [3.260, 3.283] |
| Left Temporal Lobe | | | | | |
| Left Temporal Pole | 3.143 | 0.100 | 0.002 | 3.807 [3.786, 3.828] | 3.780 [3.758, 3.801] |
| Left Inferior Temporal Gyrus | 10.472 | 0.003 ** | 0.008 | 3.084 [3.073, 3.096] | 3.057 [3.045, 3.069] |
| Left Middle Temporal Gyrus | 12.794 | 0.001 ** | 0.009 | 3.212 [3.197, 3.226] | 3.175 [3.161, 3.189] |
| Left Superior Temporal Gyrus | 29.905 | < 0.001 *** | 0.022 | 3.131 [3.119, 3.143] | 3.083 [3.071, 3.095] |
| Left Banks of the Superior Temporal Sulcus | 1.059 | 0.344 | 0.001 | 2.800 [2.787, 2.813] | 2.791 [2.778, 2.803] |
| Left Transverse Temporal Gyrus | 14.446 | 0.001 ** | 0.011 | 2.749 [2.734, 2.764] | 2.709 [2.694, 2.723] |
| Left Isthmus Cingulate Cortex | 0.052 | 0.832 | 0.000 | 2.690 [2.676, 2.704] | 2.692 [2.678, 2.706] |
| Left Parahippocampal Gyrus | 0.937 | 0.371 | 0.001 | 2.969 [2.949, 2.989] | 2.955 [2.934, 2.975] |
| Left Entorhinal Cortex | 0.193 | 0.680 | 0.000 | 3.463 [3.438, 3.487] | 3.455 [3.431, 3.479] |
| Left Fusiform Gyrus | 2.679 | 0.128 | 0.002 | 2.963 [2.954, 2.973] | 2.952 [2.943, 2.962] |
| Right Temporal Lobe | | | | | |
| Right Temporal Pole | 9.846 | 0.004 ** | 0.007 | 3.950 [3.928, 3.971] | 3.900 [3.878, 3.922] |
| Right Inferior Temporal Gyrus | 30.915 | < 0.001 *** | 0.022 | 3.113 [3.102, 3.125] | 3.066 [3.054, 3.078] |
| Right Middle Temporal Gyrus | 12.794 | 0.001 ** | 0.009 | 3.212 [3.197, 3.226] | 3.175 [3.161, 3.189] |
| Right Superior Temporal Gyrus | 29.905 | < 0.001 *** | 0.022 | 3.131 [3.119, 3.143] | 3.083 [3.071, 3.095] |
| Right Banks of the Superior Temporal Sulcus | 4.088 | 0.060 | 0.003 | 2.889 [2.875, 2.902] | 2.869 [2.856, 2.882] |
| Right Transverse Temporal Gyrus | 5.432 | 0.030 * | 0.004 | 2.775 [2.761, 2.790] | 2.751 [2.736, 2.766] |
| Right Isthmus Cingulate Cortex | 3.506 | 0.082 | 0.003 | 2.658 [2.644, 2.672] | 2.639 [2.625, 2.653] |
| Right Parahippocampal Gyrus | 1.339 | 0.285 | 0.001 | 2.931 [2.912, 2.949] | 2.915 [2.897, 2.934] |
| Right Entorhinal Cortex | 2.606 | 0.132 | 0.002 | 3.580 [3.553, 3.608] | 3.548 [3.520, 3.576] |
| Right Fusiform Gyrus | 7.774 | 0.009 ** | 0.006 | 2.966 [2.956, 2.975] | 2.947 [2.938, 2.956] |
| Left Parietal Lobe | | | | | |
| Left Paracentral Gyrus | 13.035 | 0.001 ** | 0.010 | 2.744 [2.733, 2.755] | 2.714 [2.703, 2.726] |
| Left Postcentral Gyrus | 21.727 | < 0.001 *** | 0.016 | 2.330 [2.318, 2.341] | 2.291 [2.280, 2.303] |
| Left Posterior Cingulate Cortex | 7.990 | 0.009 ** | 0.006 | 2.777 [2.766, 2.789] | 2.753 [2.742, 2.765] |

| Region | $F(1,1347)$ | FDR-corrected $p$-value | Partial $\eta^2$ | Monolingual Adjusted Mean [95% CI] | Bilingual Adjusted Mean [95% CI] |
|---|---|---|---|---|---|
| Left Precuneus | 23.599 | < 0.001*** | 0.017 | 2.714 [2.7052.724] | 2.681 [2.672, 2.691] |
| Left Superior Parietal Lobule | 37.489 | < 0.001*** | 0.027 | 2.501 [2.491, 2.511] | 2.456 [2.446, 2.466] |
| Left Supramarginal Gyrus | 13.519 | 0.001** | 0.010 | 2.869 [2.857, 2.882] | 2.836 [2.824, 2.849] |
| Left Inferior Parietal Lobule | 25.963 | < 0.001*** | 0.019 | 2.785 [2.773, 2.796] | 2.742 [2.731, 2.754] |
| Right Parietal Lobe | | | | | |
| Right Paracentral Gyrus | 13.598 | 0.001** | 0.010 | 2.747 [2.737, 2.757] | 2.720 [2.709, 2.730] |
| Right Postcentral Gyrus | 16.153 | < 0.001*** | 0.012 | 2.301 [2.290, 2.313] | 2.267 [2.256, 2.279] |
| Right Posterior Cingulate Cortex | 6.229 | 0.021* | 0.005 | 2.735 [2.724, 2.745] | 2.716 [2.705, 2.726] |
| Right Precuneus | 17.899 | < 0.001*** | 0.013 | 2.722 [2.713, 2.732] | 2.693 [2.683, 2.702] |
| Right Superior Parietal Lobule | 32.041 | < 0.001*** | 0.023 | 2.501 [2.492, 2.511] | 2.461 [2.451, 2.471] |
| Right Supramarginal Gyrus | 18.776 | < 0.001*** | 0.014 | 2.867 [2.854, 2.880] | 2.827 [2.814, 2.840] |
| Right Inferior Parietal Lobule | 28.923 | < 0.001*** | 0.021 | 2.813 [2.802, 2.824] | 2.770 [2.759, 2.781] |
| Left Occipital Lobe | | | | | |
| Left Lingual Gyrus | 0.214 | 0.673 | 0.000 | 2.193 [2.183, 2.202] | 2.189 [2.180, 2.199] |
| Left Cuneus | 12.863 | 0.001** | 0.009 | 2.060 [2.049, 2.072] | 2.031 [2.020, 2.042] |
| Left Pericalcarine Gyrus | 19.152 | < 0.001*** | 0.014 | 1.764 [1.753, 1.774] | 1.730 [1.719, 1.740] |
| Left Lateral Occipital Gyrus | 23.117 | < 0.001*** | 0.017 | 2.336 [2.324, 2.347] | 2.295 [2.283, 2.307] |
| Right Occipital Lobe | | | | | |
| Right Lingual Gyrus | 1.413 | 0.280 | 0.001 | 2.229 [2.219, 2.238] | 2.220 [2.211, 2.230] |
| Right Cuneus | 18.936 | < 0.001*** | 0.014 | 2.084 [2.073, 2.096] | 2.048 [2.037, 2.060] |
| Right Pericalcarine Gyrus | 17.488 | < 0.001*** | 0.013 | 1.753 [1.743, 1.764] | 1.721 [1.710, 1.732] |
| Right Lateral Occipital Gyrus | 21.147 | < 0.001*** | 0.015 | 2.394 [2.382, 2.405] | 2.355 [2.344, 2.367] |

*Note.*

*: FDR-corrected $p$-value < 0.05;

**: FDR-corrected $p$-value < 0.01;

***: FDR-corrected $p$-value < 0.001.



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Partial $\eta^2$ calculated as $\frac{SS_{Group}}{SS_{Group} + SS_{error}}$

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## Table 4

Unique relationships between English use, English vocabulary, and cortical thickness, controlling for age, sex, pubertal status, non-verbal IQ, household income, parent education, and handedness.

| Region | English Use | | | English Vocabulary | | |
|---|---|---|---|---|---|---|
| | **Beta (se)** | **% unique variance explained[a]** | **FDR-corrected *p*-value** | **Beta (se)** | **% unique variance explained[a]** | **FDR-corrected *p*-value** |
| Left Frontal Lobe | | | | | | |
| Left Frontal Pole | 0.001 (0.008) | 0.00% | 0.913 | 0.006 (0.004) | 0.00% | 0.310 |
| Left Medial Orbitofrontal Gyrus | −0.003 (0.004) | 0.10% | 0.576 | −0.002 (0.002) | 0.40% | 0.492 |
| Left Lateral Orbitofrontal Gyrus | 0.006 (0.004) | 0.40% | 0.196 | < 0.001 (0.002) | 0.00% | 0.872 |
| Left Pars Opercularis | 0.009 (0.004) | 1.00% | 0.057 | 0.005 (0.002) | 0.10% | 0.046 * |
| Left Pars Orbitalis | 0.008 (0.005) | 0.40% | 0.211 | 0.004 (0.003) | 0.00% | 0.273 |
| Left Pars Triangularis | 0.005 (0.004) | 0.30% | 0.268 | 0.003 (0.002) | 0.50% | 0.248 |
| Left Rostral Middle Frontal Gyrus | 0.007 (0.004) | 0.60% | 0.142 | 0.006 (0.002) | 0.10% | 0.032 * |
| Left Caudal Middle Frontal Gyrus | 0.008 (0.004) | 0.80% | 0.085 | 0.007 (0.002) | 0.00% | 0.011 * |
| Left Superior Frontal Gyrus | 0.014 (0.004) | 2.10% | 0.014 * | 0.004 (0.002) | 0.00% | 0.193 |
| Left Rostral Anterior Cingulate Cortex | 0.009 (0.005) | 0.40% | 0.188 | 0.005 (0.003) | 0.00% | 0.193 |
| Left Caudal Anterior Cingulate Cortex | 0.019 (0.006) | 1.60% | 0.015 * | 0.005 (0.003) | 0.00% | 0.248 |
| Left Precentral Gyrus | 0.010 (0.003) | 1.20% | 0.040 * | 0.005 (0.002) | 0.00% | 0.041 * |
| Left Insula | 0.006 (0.003) | 0.50% | 0.172 | < 0.001 (0.002) | 0.00% | 0.918 |
| Right Frontal Lobe | | | | | | |
| Right Frontal Pole | −0.006 (0.008) | 0.10% | 0.531 | 0.006 (0.004) | 0.10% | 0.309 |
| Right Medial Orbitofrontal Gyrus | −0.002 (0.004) | 0.00% | 0.668 | −0.002 (0.002) | 0.00% | 0.516 |
| Right Lateral Orbitofrontal Gyrus | −0.001 (0.004) | 0.00% | 0.892 | < 0.001 (0.002) | 0.00% | 0.940 |
| Right Pars Opercularis | 0.008 (0.004) | 0.70% | 0.105 | 0.004 (0.002) | 0.10% | 0.096 |
| Right Pars Orbitalis | 0.011 (0.005) | 0.70% | 0.133 | 0.003 (0.003) | 0.00% | 0.336 |
| Right Pars Triangularis | 0.008 (0.004) | 0.60% | 0.142 | 0.004 (0.002) | 0.00% | 0.193 |
| Right Rostral Middle Frontal Gyrus | 0.005 (0.003) | 0.40% | 0.196 | 0.003 (0.002) | 0.00% | 0.193 |
| Right Caudal Middle Frontal Gyrus | 0.006 (0.004) | 0.40% | 0.196 | 0.003 (0.002) | 0.10% | 0.295 |
| Right Superior Frontal Gyrus | 0.007 (0.004) | 0.60% | 0.142 | 0.001 (0.002) | 0.00% | 0.724 |

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| Region | English Use | | | English Vocabulary | | |
|---|---|---|---|---|---|---|
| | Beta (se) | % unique variance explained[a] | FDR-corrected *p*-value | Beta (se) | % unique variance explained[a] | FDR-corrected *p*-value |
| Right Rostral Anterior Cingulate Cortex | 0.001 (0.005) | 0.00% | 0.892 | 0.004 (0.003) | 0.00% | 0.310 |
| Right Caudal Anterior Cingulate Cortex | 0.011 (0.005) | 0.60% | 0.142 | −0.003 (0.003) | 0.10% | 0.485 |
| Right Precentral Gyrus | 0.012 (0.004) | 1.70% | 0.014* | 0.001 (0.002) | 0.00% | 0.609 |
| Right Insula | 0.004 (0.004) | 0.20% | 0.333 | 0.003 (0.002) | 0.00% | 0.248 |
| <u>Left Temporal Lobe</u> | | | | | | |
| Left Temporal Pole | 0.003 (0.007) | 0.00% | 0.745 | 0.007 (0.004) | 0.00% | 0.248 |
| Left Inferior Temporal Gyrus | 0.011 (0.004) | 1.10% | 0.046* | 0.005 (0.002) | 0.00% | 0.087 |
| Left Middle Temporal Gyrus | 0.008 (0.005) | 0.40% | 0.196 | 0.007 (0.003) | 0.00% | 0.070 |
| Left Superior Temporal Gyrus | 0.012 (0.005) | 1.10% | 0.046* | 0.009 (0.002) | 0.10% | 0.010* |
| Left Banks of the Superior Temporal Sulcus | 0.009 (0.004) | 0.80% | 0.116 | 0.002 (0.002) | 0.40% | 0.613 |
| Left Transverse Temporal Gyrus | 0.002 (0.005) | 0.10% | 0.723 | 0.004 (0.003) | 0.10% | 0.295 |
| Left Isthmus Cingulate Cortex | 0.006 (0.005) | 0.20% | 0.343 | −0.002 (0.002) | 0.00% | 0.574 |
| Left Parahippocampal Gyrus | 0.012 (0.007) | 0.50% | 0.172 | 0.001 (0.004) | 0.10% | 0.884 |
| Left Entorhinal Cortex | 0.016 (0.008) | 0.60% | 0.142 | −0.001 (0.004) | 0.10% | 0.869 |
| Left Fusiform Gyrus | 0.001 (0.003) | 0.00% | 0.837 | 0.001 (0.002) | 0.10% | 0.711 |
| <u>Right Temporal Lobe</u> | | | | | | |
| Right Temporal Pole | < 0.001 (0.008) | 0.00% | 0.977 | 0.005 (0.004) | 0.10% | 0.346 |
| Right Inferior Temporal Gyrus | 0.006 (0.004) | 0.40% | 0.196 | 0.007 (0.002) | 0.00% | 0.024* |
| Right Middle Temporal Gyrus | 0.014 (0.005) | 1.20% | 0.040* | 0.007 (0.003) | 0.10% | 0.041* |
| Right Superior Temporal Gyrus | 0.008 (0.004) | 0.50% | 0.160 | 0.008 (0.002) | 0.40% | 0.010* |
| Right Banks of the Superior Temporal Sulcus | 0.010 (0.004) | 0.80% | 0.093 | 0.005 (0.002) | 0.10% | 0.135 |
| Right Transverse Temporal Gyrus | 0.008 (0.005) | 0.40% | 0.196 | −0.003 (0.003) | 0.10% | 0.474 |
| Right Isthmus Cingulate Cortex | < 0.001 (0.005) | 0.00% | 0.956 | 0.001 (0.002) | 0.00% | 0.869 |
| Right Parahippocampal Gyrus | 0.020 (0.006) | 1.50% | 0.015* | 0.001 (0.003) | 0.10% | 0.869 |
| Right Entorhinal Cortex | 0.008 (0.009) | 0.10% | 0.493 | 0.004 (0.005) | 0.00% | 0.528 |
| Right Fusiform Gyrus | 0.003 (0.003) | 0.20% | 0.453 | 0.003 (0.002) | 0.10% | 0.273 |
| <u>Left Parietal Lobe</u> | | | | | | |
| Left Paracentral Gyrus | 0.005 (0.004) | 0.30% | 0.244 | 0.003 (0.002) | 0.00% | 0.273 |

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| Region | English Use | | | English Vocabulary | | |
|---|---|---|---|---|---|---|
| | Beta (se) | % unique variance explained[a] | FDR-corrected *p*-value | Beta (se) | % unique variance explained[a] | FDR-corrected *p*-value |
| Left Postcentral Gyrus | 0.004 (0.004) | 0.20% | 0.352 | 0.004 (0.002) | 0.00% | 0.107 |
| Left Posterior Cingulate Cortex | 0.002 (0.004) | 0.00% | 0.680 | 0.003 (0.002) | 0.00% | 0.318 |
| Left Precuneus | 0.006 (0.003) | 0.50% | 0.172 | 0.001 (0.002) | 0.20% | 0.869 |
| Left Superior Parietal Lobule | 0.011 (0.003) | 1.50% | 0.015* | 0.001 (0.002) | 0.00% | 0.869 |
| Left Supramarginal Gyrus | 0.010 (0.004) | 1.00% | 0.071 | 0.006 (0.002) | 0.00% | 0.046* |
| Left Inferior Parietal Lobule | 0.012 (0.004) | 1.70% | 0.014* | 0.001 (0.002) | 0.10% | 0.696 |
| <u>Right Parietal Lobe</u> | | | | | | |
| Right Paracentral Gyrus | 0.006 (0.003) | 0.50% | 0.188 | < 0.001 (0.002) | 0.10% | 0.872 |
| Right Postcentral Gyrus | 0.002 (0.004) | 0.10% | 0.668 | 0.004 (0.002) | 0.00% | 0.193 |
| Right Posterior Cingulate Cortex | 0.006 (0.003) | 0.50% | 0.172 | 0.003 (0.002) | 0.00% | 0.273 |
| Right Precuneus | 0.005 (0.003) | 0.30% | 0.211 | < 0.001 (0.002) | 0.00% | 0.885 |
| Right Superior Parietal Lobule | 0.006 (0.003) | 0.60% | 0.142 | < 0.001 (0.002) | 0.00% | 0.918 |
| Right Supramarginal Gyrus | 0.008 (0.004) | 0.60% | 0.143 | 0.006 (0.002) | 0.00% | 0.041* |
| Right Inferior Parietal Lobule | 0.012 (0.004) | 1.70% | 0.014* | 0.003 (0.002) | 0.00% | 0.287 |
| <u>Left Occipital Lobe</u> | | | | | | |
| Left Lingual Gyrus | −0.001 (0.003) | 0.00% | 0.892 | −0.002 (0.002) | 0.00% | 0.347 |
| Left Cuneus | 0.003 (0.004) | 0.10% | 0.609 | −0.003 (0.002) | 0.10% | 0.310 |
| Left Pericalcarine Gyrus | −0.001 (0.004) | 0.00% | 0.771 | 0.001 (0.002) | 0.00% | 0.869 |
| Left Lateral Occipital Gyrus | 0.009 (0.004) | 0.80% | 0.093 | 0.004 (0.002) | 0.30% | 0.193 |
| <u>Right Occipital Lobe</u> | | | | | | |
| Right Lingual Gyrus | −0.003 (0.003) | 0.10% | 0.500 | −0.001 (0.002) | 0.00% | 0.833 |
| Right Cuneus | 0.005 (0.004) | 0.30% | 0.268 | 0.001 (0.002) | 0.40% | 0.872 |
| Right Pericalcarine Gyrus | 0.001 (0.003) | 0.00% | 0.892 | 0.003 (0.002) | 0.00% | 0.196 |
| Right Lateral Occipital Gyrus | 0.007 (0.004) | 0.50% | 0.172 | 0.003 (0.002) | 0.00% | 0.310 |

*Note.*

*: FDR-corrected *p*-value < 0.05.

[a] Based on partial $r^2$, calculated from a partial Pearson's *r* correlation.