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Neuroanatomical Evidence in Support of the Bilingual Advantage Theory

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Abstract

The “bilingual advantage” theory stipulates that constant selection and suppression between 2 languages results in enhanced executive control (EC). Behavioral studies of EC in bilinguals have employed wide-ranging tasks and report some conflicting results. To avoid concerns about tasks, we employed a different approach, measuring gray matter volume (GMV) in adult bilinguals, reasoning that any EC-associated benefits should manifest as relatively greater frontal GMV. Indeed, Spanish-English-speaking bilinguals exhibited greater bilateral frontal GMV compared with English-speaking monolinguals. Was this observation attributable to the constant selection and inhibition of 2 spoken languages? To answer this question, we drew on bimodal bilinguals of American Sign Language (ASL) and English who, unlike unimodal bilinguals, can simultaneously use both languages and have been shown not to possess the EC advantage. In this group, there was no greater GMV when compared with monolinguals. Together these results provide neuroanatomical evidence in support of the bilingual advantage theory.

Key words: bilingual advantage, bimodal bilingual, executive control, unimodal bilingual, voxel-based morphometry

Introduction

Behavioral studies have revealed superior performance by bilinguals relative to monolinguals on tasks of executive control (EC; [Peal and Lambert 1962](#); [Bialystok 1999](#); [Carlson and Meltzoff 2008](#); [Costa et al. 2008](#)). This so-called bilingual advantage is thought to be the result of a bilingual’s constant need to select the intended language when speaking ([Abutalebi and Green 2007](#); [Bialystok et al. 2012](#)), while suppressing the non-target language, which is “active” even if not used (demonstrated via cross-language interaction in priming studies [[Kroll et al. 2008](#)]). A remarkable aspect of the bilingual advantage is that it is not constrained to language tasks but generalizes to non-verbal tasks of EC such as attention shifting, inhibition, target selection, and conflict resolution ([Bialystok et al. 2012](#)).

However, the theory is not without controversy. Not all bilingual studies show heightened EC ([Duñabeitia et al. 2013](#); [Paap and Greenberg 2013](#)). This inconsistency has been attributed to the type of EC task employed and, further, to variations within these ([Bialystok et al. 2012](#)). For example, studies utilizing adaptations of the Simon Task ([Simon and Rudell 1967](#)) have shown a bilingual advantage ([Bialystok et al. 2004](#); [Bialystok, Craik et al. 2005](#); [Bialystok, Martin et al. 2005](#); [Martin-Rhee and Bialystok 2008](#)). On the other hand, the use of a modified Stroop Task ([Stroop 1935](#)) involving the naming of pictures (e.g., “day” or “night”) did not elicit a bilingual advantage ([Martin-Rhee and Bialystok 2008](#)). This might be due to the linguistic nature of this task, inadvertently putting the bilinguals at a disadvantage due to their weakness in lexical access (e.g., for picture naming

[Gollan et al. 2005]) and verbal fluency (Rosselli et al. 2000). It has been argued that the Simon Arrows Task avoids this kind of confound (Martin-Rhee and Bialystok 2008) and, as such, has been shown to demonstrate the bilingual advantage for conditions that require high monitoring (Bialystok 2006). Similar nuances and inconsistencies exist for other tasks. The Flanker Task (Eriksen and Eriksen 1974) did not reveal accuracy or reaction time differences between bilinguals and monolinguals (Luk et al. 2010). Conversely, a related task, the Attentional Network Task (ANT; Fan et al. 2002), was shown to elicit a bilingual advantage, with bilinguals demonstrating an advantage in response time and efficiency of response switching (Costa et al. 2008). However, this finding is also dependent on the inclusion of conditions that require high monitoring (Costa et al. 2009). Together, while there are numerous tests associated with EC, they tap into different aspects of EC and to varying degrees. Furthermore, the assumption that each of these tasks maps onto a single cognitive process (e.g., inhibition) that explains the differences in performance between bilinguals and monolinguals may be problematic. Instead, bilingualism may represent a more general functional reconfiguration that is manifest in multiple processes (Kroll and Bialystok 2013). Taken together, this poses a challenge for research studies and clinical evaluation (Burgess et al. 1998) of EC functions and has been a primary reason for uncertainty about the bilingual advantage theory.

Given the concern around the choice of EC task used to elicit the bilingual advantage, we employed a different approach, this time measuring and comparing gray matter volume (GMV) in adult bilinguals and monolinguals, without concern for any specific measures of EC. GMV differences should provide an objective anatomical indication of any accumulated experience-dependent changes due to cognitive control in bilinguals compared with monolinguals. We measured whole-brain GMV to capture the breadth of anatomical regions connected with prefrontal cortex (Fuster 2001), predicting that Spanish-English bilinguals would show more GMV in these EC areas compared with English-speaking monolinguals, much like other cases of lifelong experiences shaping brain structure. Examples of prior studies that have shown GMV differences between specific groups include those with different vocational experiences, such as taxi drivers, who manifested more GMV in the hippocampus (Maguire et al. 2000). Altered sensory experiences such as blindness and deafness have also been shown to reflect in gray matter differences when compared with sighted or hearing comparison groups, respectively (Emmorey et al. 2003; Noppeney et al. 2005; Smith et al. 2011; Olulade et al. 2014), and longitudinal studies using simple training protocols such as juggling have shown induced GMV changes in extrastriate visual cortex (Draganski et al. 2004). Based on these, we expected to find greater GMV in the bilinguals in regions that are known to be involved in EC, specifically dorsolateral prefrontal and parietal cortices (Bunge et al. 2002; Derrfuss et al. 2004; Cole and Schneider 2007).

While GMV has been studied in bilinguals before, these prior investigations have largely involved participants who acquired their second language relatively late, usually after age 6, and often not until adulthood (Mechelli et al. 2004; Zou et al. 2012). Because brain anatomy in bilinguals is modulated by the age at which the second language was first acquired (Mechelli et al. 2004), the present study included only “early” bilinguals who acquired their languages before age 6. As such, these adult bilinguals not only acquired both their languages at a young age but also have experienced bilingualism, and any EC advantages this may confer, for most of their lives.

Another pressing question is whether it is the constant need to decide and select which language to use that enhances EC, which is the premise of the bilingual advantage theory. It is conceivable that other aspects of being bilingual, such as the presence of 2 languages, which brings with it a large vocabulary (Costa and Sebastián-Gallés 2014), could also lead to differences in GMV. To address whether selection of the target language coupled with inhibition/suppression of the non-target language during speech, which is the proposed mechanism of the bilingual advantage (Emmorey et al. 2008; Bialystok et al. 2012), is indeed the source of any differences, we also conducted a GMV comparison study in bilinguals of American Sign Language (ASL) and spoken English. These ASL-English *bimodal* bilinguals (2 languages in different modalities) can sign and speak simultaneously (whereas *unimodal* bilinguals cannot simultaneously produce their 2 spoken languages), thereby experiencing less conflict resolution. In fact, ASL-English bimodal bilinguals have been shown not to exhibit the bilingual advantage, demonstrating EC performance indistinguishable from monolinguals (Emmorey et al. 2008). Specifically, Emmorey and colleagues found superior performance on a Flanker Task in unimodal but not bimodal bilinguals compared with monolinguals. Just as in this behavioral work, our bimodal bilinguals were hearing native users of ASL born to deaf parents, sometimes referred to as children of deaf adults (CODAs). Like our Spanish-English unimodal bilinguals, they were raised with 2 different languages, but unlike the Spanish-English bilinguals, their 2 languages utilize different modalities. The study of this group of bimodal bilinguals allowed us to disambiguate anatomical differences observed in the unimodal Spanish-English bilinguals (relative to monolinguals of English), due to forced language selection, from general effects of bilingualism (i.e., representation of 2 languages), as these are common to both types of bilinguals. As such, the comparison of the bimodal bilinguals (ASL-English) with monolinguals was not expected to yield the anatomical differences anticipated in frontal EC regions of bilinguals of 2 spoken languages compared with monolinguals, because these bilinguals do not face the conflict to the same degree as unimodal bilinguals.

It has been shown that the bilingual advantage holds independently of cultural differences. Specifically, Bialystok and Viswanathan, when comparing performance on a task of EC between bilingual children from India and Canada and monolingual children from Canada, observed the bilingual advantage in both groups of bilingual children relative to the monolinguals (Bialystok and Viswanathan 2009). Notably, performance did not differ between the 2 groups of bilingual children. The same is true for socioeconomic status (SES): it has been found that the bilingual advantage is present in low-SES immigrant bilingual children (Engel de Abreu et al. 2012), just as it is in high-SES bilinguals (Oller and Pearson 2002; Martin-Rhee and Bialystok 2008; Bialystok 2009). While it appears that the bilingual advantage is not restricted by socioeconomic or cultural factors, some have questioned whether findings in prior studies of EC in (unimodal) bilinguals could be attributed to cultural differences and SES (Morton and Harper 2007). To avoid any ambiguity, we recruited both of our bilingual groups as well as the monolingual group from university campuses and also ensured that our participants reported similar levels of education for their parents (a good indicator of SES). An advantage of studying young adults is that it permits the opportunity to study those with significant experience with their 2 languages. Further, unlike children, their frontal lobes are not in the midst of development (Giedd et al. 1999; Klingberg et al. 1999) but are close to being mature, thereby offering a relatively stable situation for study.

Materials and Methods

Participants

Forty-five healthy young adults were included in this study. None reported a history of neurological or psychological disorder. All participants were recruited via fliers placed on the campuses of Georgetown University and Gallaudet University in Washington, DC, and all had completed at least 1 year of university. Each group, *monolinguals* (English), *unimodal bilinguals* (Spanish-English), and *bimodal bilinguals* (ASL-English) consisted of 15 participants. Monolinguals (7 female and 8 male) were native speakers of English. Unimodal bilinguals (9 female and 6 male) were native speakers of Spanish and English and learned both languages before the age of 6 years. A subset of these participants were included in a functional MRI study on the neural basis of reading in bilinguals (Jamal et al. 2012). Bimodal bilinguals (11 female and 4 male) were native users of ASL and English. These hearing participants were born to deaf parents and also learned both languages before the age of 6 years. A subset of these participants were included in a prior voxel based morphometry (VBM) study of language and deafness (Olulade et al. 2014).

Participant characteristics are shown in Table 1. All participants had single-word reading skills within or above the normal range (we used an age-standardized score of 80 or above) on the Woodcock-Johnson III Basic Reading Composite Cluster (Woodcock et al. 2001). The bilingual groups were matched to the monolingual group on reading (two-sample *t*-tests; $P > 0.05$) to rule out the possibility of any GMV differences being attributed to reading ability (He et al. 2013).

All participants completed questionnaires on their language history, language exposure, language use, and their own evaluation of their language proficiency. Both groups of bilinguals reported current use of both of their languages, with high proficiency and frequent daily use of both languages (i.e., Spanish and English in unimodal bilinguals, and ASL and English in bimodal bilinguals). The unimodal bilinguals grew up with native Spanish-speaking parents and therefore had Spanish as a first language along with English. The bimodal bilinguals are CODAs who grew up with deaf parents and had ASL as a first language along with spoken English. Using slightly different rating instruments, both groups of bilinguals were asked to rate their proficiency on their non-English language. Both groups reported high proficiency. Specifically, Spanish-English bilinguals reported an average proficiency of 6.8 and 6.5 (on a scale of 1 to 7) in listening comprehension and speaking of Spanish, respectively. ASL-English bilinguals reported an average proficiency of 4.6 and 4.3 (on a scale of 1 to 5) on their current fluency for receptive and expressive ASL, respectively. When the rating scales were adjusted for the sake of comparison, the 2 groups did not

differ in their proficiency (two-sample *t*-test; $P > 0.2$). All participants were college students (past or present), which ensured that both bilingual groups were culturally similar to the monolingual group. Further, based on the information provided by the participants, we were able to determine that both bilingual groups were of similar socioeconomic standing, measured via their reporting of parental education level. In the ASL-English bilingual group, all but 1 of the 30 parents of the 15 participants completed high school. Twenty of these 30 parents took college-level courses, with 6 of these completing a graduate degree (master's or Ph.D.). In the Spanish-English bilinguals, all but 1 of the 27 parents of the participants (information on 3 was missing) completed high school. Twenty-one of these 27 parents took college-level courses, with 6 of these completing a graduate degree (medical school, master's, or Ph.D.).

Written informed consent was obtained from all participants at the beginning of the study, and all protocols were approved by the Georgetown University and the Gallaudet University Institutional Review Boards.

MRI Data Acquisition

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

MRI Data Analysis

Analysis of images was performed in SPM8 using the automated VBM technique (Ashburner and Friston 2000) and methods outlined by Ashburner (<http://www.fil.ion.ucl.ac.uk/spm/>). To reduce inter-subject variability in spatial location, images from all participants were manually re-aligned to the anterior commissures prior to preprocessing. Subsequent preprocessing of images first involved co-registration to the white matter template, followed by segmentation of the gray matter using the "New Segment" toolbox (Ashburner and Friston 2005). Images were next co-registered to a custom study-specific template and then spatially normalized to the Montreal Neurological Institute (MNI) stereotaxic space via affine registration of the generated template to the MNI template using DARTEL (Ashburner 2007). During this step, the "modulation" option was selected so that the parameter of interest in observed differences was tissue volume rather than tissue density. Images were inspected to ensure accuracy of this normalization procedure. To reduce anatomical variability, the images were smoothed with an isotropic Gaussian kernel of 10 mm Full Width at Half Maximum. Finally, images were intensity thresholded at 0.2 to reduce edge artifacts.

MRI Statistical Analysis

Statistical analysis of gray matter images was performed using SPM8. Two separate between-group comparisons of gray matter images were performed using two-sample *t*-tests. First, GMV was compared between the unimodal bilinguals and the monolinguals. For the images submitted to this analysis, the study-specific template utilized in the normalization procedure during preprocessing was generated using only the participants in these 2 groups. Next, a comparison was made between the bimodal bilinguals and the same group of monolinguals, again via a two-sample *t*-test. A different template was generated using

Table 1 Participant demographic information

	Unimodal bilinguals	Bimodal bilinguals	Monolinguals
F/M	9/6	11/4	7/8
Age			
Mean ± std	22.3 ± 3.2	26.4 ± 6.1	25.9 ± 6.0
Range	(18.4–28.6)	(19.2–39.7)	(18.6–41.8)
Basic reading ^a			
Mean ± std	104.0 ± 6.4	105.3 ± 8.4	108.9 ± 7.3
Range	(96–117)	(92–116)	(93–121)

^aWoodcock-Johnson III Tests of Achievement.

only participants in these groups and utilized during normalization of the images submitted to this analysis. In both analyses, we tested for areas showing greater GMV in the bilinguals relative to the monolinguals and vice versa. Images were thresholded at a height level of $P < 0.005$ and corrected for multiple comparisons using a non-stationary cluster correction (Hayasaka et al. 2004) at a corrected threshold of $P < 0.05$. Clusters were rendered onto the MNI anatomical template using SUMA (Saad and Reynolds 2012). While total intracranial volume (TIV: sum of whole-brain gray matter, white matter, and cerebrospinal fluid) did not differ between the groups, this parameter was included as a covariate of no interest in the analysis to ensure accurate inference of regional variation in gray matter (Peelle et al. 2012).

Results

Unimodal Bilinguals (Spanish-English) versus Monolinguals (English)

Relative to the English-speaking monolinguals, the Spanish-English bilinguals exhibited greater GMV bilaterally (Fig. 1a, Table 2), including areas in dorsolateral prefrontal cortex (DLPFC) and parietal cortex, previously shown to make up the “executive-control network” (Seeley et al. 2007). Specifically, unimodal bilinguals had greater GMV than monolinguals most noticeably in right precentral (BA 4) gyrus (see Table 2 for MNI coordinates), extending both anteriorly into the inferior frontal gyrus (BA 44/45) and frontal operculum (BA 46; nearest subpeak MNI coordinate: $x, y, z = 38, 8, 24$), as well as posteriorly into inferior parietal cortex (BA 39/40; peak MNI: $45, -46, 33$). A second right hemisphere cluster was located in the middle frontal gyrus (BA 11) extending into the medial and superior frontal gyri (BA 10/11), and a third in the superior temporal gyrus (BA 22), extending into the middle temporal gyrus (BA 21/22).

In the left hemisphere, the areas were not as extensive, with the largest cluster located in the middle frontal gyrus (BA 10)

extending into inferior frontal gyrus (dorso- and ventrolateral prefrontal cortices; DLPFC/VLPFC – BA 46/47). The second cluster was located at the most posterior aspect of the brain in left occipital lobe’s middle (BA 18), inferior (BA 18), and superior occipital gyri (BA 19), and the cuneus (BA 19), extending into the posterior aspects of the middle temporal gyrus (BA 19). A third, smaller cluster was found in the left precentral gyrus (BA 4).

The opposite contrast yielded greater GMV for the monolinguals relative to the unimodal bilinguals primarily in the left cerebellum, extending into the left occipital lobe including the cuneus, lingual gyrus (BA 18/19), and fusiform gyrus (BA 19; peak MNI: $-2, -70, -11$), and the right cerebellum (peak MNI: $40, -69, -39$). Clusters were also observed in the bilateral parahippocampal (BA 34/35) gyri, extending into the hippocampus, amygdala, and fusiform gyrus (BA 20) in the left hemisphere and into the cerebellum in the right hemisphere. Finally, greater GMV was found for the monolinguals in the right middle temporal gyrus (BA 21) extending into the inferior temporal (BA 20/21) and fusiform (BA 20) gyri.

Bimodal Bilinguals (ASL-English) versus Monolinguals (English)

No areas of greater GMV were observed when the ASL-English bilinguals were compared with the group of English-speaking monolinguals (Fig. 1b; Table 2). On the other hand, monolinguals had greater GMV in the right precentral gyrus (BA 4), extending into the postcentral gyrus (BA 3).

Discussion

Behavioral studies have demonstrated superior performance on executive function for bilinguals of 2 spoken languages relative to monolinguals (Peal and Lambert 1962; Bialystok 1999; Carlson and Meltzoff 2008; Costa et al. 2008), and these have been

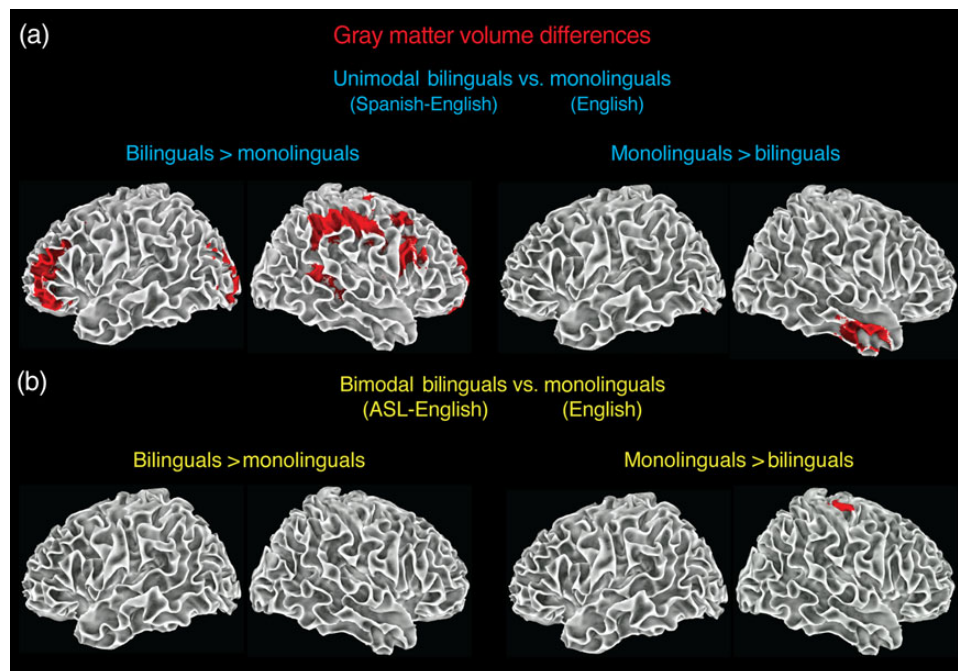


Figure 1. GMV Comparisons. (a) Unimodal bilinguals revealed greater GMV than monolinguals in bilateral frontal and right parietal regions. (b) Bimodal bilinguals did not reveal any areas of greater GMV. Significant clusters were generated using a threshold of $P < 0.005$, with a non-stationary correction for multiple comparisons at a threshold of $P < 0.05$.

Table 2 MNI coordinates for maxima of GMV differences

MNI coordinates			Anatomical region	BA	Z	k
x	y	z				
Unimodal bilinguals (Spanish-English) versus monolinguals (English)						
Bilinguals > monolinguals						
-24	-97	6	l. middle occipital gyrus	18	4.32	2060
			l. inferior and superior occipital, middle temporal gyri and cuneus	18/19		
-36	-21	41	l. precentral gyrus	4	3.99	93
			l. postcentral gyrus	4		
-40	42	19	l. middle frontal gyrus	10	4.39	3577
			l. inferior frontal gyrus	46/47		
45	-48	12	r. superior temporal gyrus	22	4.05	1417
			r. middle temporal gyrus	21/22		
44	-21	45	r. precentral gyrus	4	4.82	10 410
			r. supramarginal, angular, postcentral gyri, and inferior parietal lobule	2/3/4/39/40		
			r. middle and inferior frontal gyri, frontal operculum	8/9/44/45/46		
21	69	12	r. middle frontal gyrus	11	4.27	4102
			r. medial and superior frontal gyri	10/11		
Monolinguals > bilinguals						
-21	-66	-41	l. cerebellum		5.71	31 514
			l. cuneus, lingual and fusiform gyri, and r. cerebellum	18/19		
-38	-12	-23	l. parahippocampal gyrus	34	4.53	2586
			l. hippocampus, amygdala, and fusiform gyrus	20		
62	4	-30	r. middle temporal gyrus	21	4.14	2108
			r. inferior temporal and fusiform gyri	20/21		
15	6	-36	r. parahippocampal gyrus	35	4.13	484
			r. cerebellum			
Bimodal bilinguals (ASL-English) versus monolinguals (English)						
No Significant Clusters						
Monolinguals > bilinguals						
46	-31	64	r. precentral gyrus	4	4.34	487
			r. postcentral gyrus	3		

Note: Boldface entries indicate anatomical location of cluster peak; non-boldface entries indicate anatomical locations of cluster extent.

attributed to the long-term experiences with selection and inhibition of their 2 languages (Bialystok et al. 2012). Specifically, there is a consistent need for bilinguals to control their 2 languages in terms of identifying and monitoring the language used by the interlocutor, selection of the appropriate target language, and inhibition or suppression of the non-target language, all of which are thought to lead to the advantages in EC observed in bilinguals (Bialystok et al. 2012). The purpose of this study was to use a measure of brain anatomy to address the bilingual advantage theory. We reasoned that lifelong differences in EC enforced by the management of 2 spoken languages would be reflected in greater GMV, analogous to other observations of experience-dependent plasticity involving cognition (Maguire et al. 2000). Indeed, the comparison between Spanish-English bilinguals and English monolinguals revealed greater GMV for the bilinguals in right DLPFC and parietal cortex, as well as left DLPFC and VLPFC. These areas are members of an executive-control network as demonstrated by functional neuroimaging studies (Bunge et al. 2002; Derffuss et al. 2004; Luk et al. 2012), including some examining functional connectivity (Cole and Schneider 2007; Seeley et al. 2007). Further, gray matter in these areas has been shown to correlate with performance on tasks of EC (Luks et al. 2010) and to differ in disorders of executive function (Seidman et al. 2005).

Next, to address the question of whether these differences can be attributed to the constraint of bilinguals' 2 spoken languages, which forces language selection (i.e., the proposed mechanism by which bilingual's EC is promoted [Emmorey et al. 2008]), we examined ASL-English bimodal bilinguals. We found no GMV differences

in this group compared with monolinguals, demonstrating that bilinguals whose languages involve different modalities do not show anatomical evidence indicative of heightened experience in EC. As such, our findings of anatomical differences in frontal-parietal cortices of unimodal bilinguals fit well with prior behavioral work demonstrating an advantage in EC in unimodal bilinguals (whose 2 languages both rely on the spoken modality) but not bimodal bilinguals (Emmorey et al. 2008). This provides important insight into the mechanism of the bilingual advantage, namely, that it does emanate from a need for unimodal bilinguals (who represent the bilinguals previously studied in the context of the bilingual advantage theory) to control their 2 spoken languages.

Previous studies examining structural differences between bilinguals and monolinguals have mostly involved bilinguals who learned their second language later in life, after age 6, and usually even later as adults (Mechelli et al. 2004; Grogan et al. 2012; Stein et al. 2012; Zou et al. 2012). Such late second language learners are not subjected to the lifelong bilingual experience as are the bilinguals studied here. Importantly, when specifically addressing the effect of age of second language acquisition on brain anatomy, there are direct correlations between age at which the second language was acquired and GMV (Mechelli et al. 2004), highlighting the importance of restricting our investigation to early bilinguals who learned both languages before the age of 6. The use of early bilinguals circumvents another potential pitfall, which is that people who deliberately learn a second language might have specific cognitive skills that attract them to and facilitate their second language learning.

As a consequence, anatomical differences in these bilinguals compared with monolinguals may be a reflection of these “innate” abilities, rather than a bilingual experience per se. Our study involved bilinguals whose language learning was the result of their cultural situation, such as learning their parents’ languages or that spoken in their country of residence.

An advantage of the study of Spanish-English and ASL-English bilinguals is that both groups have mostly experienced either Spanish or ASL as a home language and English as the dominant language for education. As such, they could be described as “heritage speakers.” The cognitive consequences of bilingualism specifically in heritage speakers have been a topic of discussion (Lipka et al. 2005; Valdés 2005), and it is important that the 2 groups are similar in this regard. Further, bilinguals engage in various patterns of conversational exchange depending on the social and situational context. These traditional bilingual behaviors have been examined in both unimodal and bimodal bilinguals (Berent 2004). Green and Abutalebi (2013) have examined these specifically with regard to their demands on language control processes. They describe 3 specific interactional contexts for bilinguals: 1) a single-language context, in which each language is used in different distinctive environments (e.g., work versus home), 2) a dual-language context in which each language is used, potentially within a single conversation, necessitating switching between languages, and 3) a code-switching context in which the 2 languages are interleaved in single utterances and adapted from each other. Importantly, relative to monolinguals, bilinguals draw on control processes to some extent in the single-language context, but mostly in the dual-language context, relying on goal maintenance, conflict monitoring, interference suppression, selective response inhibition, and task engagement and disengagement (Green and Abutalebi 2013). While there are individual differences among all of our participants, there is no evidence to suggest that on average 1 of our bilingual groups engaged significantly more frequently than the other in any of these 3 specific interactional contexts. During childhood, both groups frequently experienced the single-language context, with English at school and in formal settings, and ASL or Spanish at home. With increasing age, both groups had increasing opportunities for a dual-language context. At the time of this study, subjects from both groups report using both languages frequently, and their situations (e.g., home, campus) provided opportunities for single- and dual-language contexts. The third interactional context, code-switching, makes fewer demands on cognitive control mechanisms in bilinguals (relative to monolinguals [Green and Abutalebi 2013]). Code-switching is universal to fluent speakers of 2 languages and is thought to be modulated by a variety of specific social and discourse constraints (Belazi et al. 1994; Milroy and Muysken 1995). There are a variety of signing styles, but it is not known whether hearing signers would engage in more code-switching than our Spanish-English bilinguals, and it is unlikely that such opportunities would come at the cost of the other 2 interactional contexts. Taken together, it seems safe to assume that generally, the bilingual behaviors of our 2 groups are similar, even though the interactional contexts are more difficult to characterize in bimodal bilinguals (Berent 2004). Furthermore, differences in language proficiency can potentially introduce confounds into the comparisons made between bilinguals, particularly with respect to brain-based measurements in EC areas (e.g., Perani et al. 1998; Abutalebi et al. 2013). We avoided this problem, as both of our bilingual groups reported being equally proficient in English as well as in their other language (i.e., Spanish or ASL).

A recent review evaluating the merits of the bilingual advantage theory raised concerns about the reliability of the effect,

given that it is not robust across all tasks and subject ages (Costa and Sebastián-Gallés 2014). Here, we included only young adults and early bilinguals and circumvented the problem of task entirely by relying on GMV as the dependent variable, assuming it is reflective of cognitive mechanisms that have been implemented to a greater degree in unimodal bilinguals. While this assumption may not hold for all brain regions (some regions may inherently show little or no experience-dependent growth in GMV even with significant experience), our results suggest validity to this approach, given the overlap in the areas of GMV difference in (unimodal) bilinguals with those involved in EC. Our findings align well with prior studies and previous explanations of the neurobiological mechanism of the bilingual advantage. For example, Mechelli and colleagues, using a similar measure, found more gray matter density in right (and left) parietal cortex in early bilinguals (who acquired both languages before the age of 5 years) relative to monolinguals (Mechelli et al. 2004). Interestingly, functional brain imaging studies have demonstrated activation of EC areas in bilinguals during both linguistic and nonlinguistic task switching. As summarized by Abutalebi and Green (2007), activation of the bilateral prefrontal cortex, anterior cingulate cortex, and supramarginal gyrus has been observed during language switching in bilinguals. Similar areas, primarily localized to the left hemisphere, were identified in a meta-analysis of 10 neuroimaging studies of language switching in bilinguals (Luk et al. 2012). These studies support the hypothesis that bilingual language control affects cognitive control via the involvement of language areas (Garbin et al. 2010) and that these areas become involved even for nonlinguistic tasks, such as switching between attending to the color or shape of objects (Rodríguez-Pujadas et al. 2013). While we report GMV differences in left inferior frontal cortex, the most extensive differences between our unimodal bilinguals and monolinguals reside in right hemisphere DLPFC and parietal areas aligned with the EC network (Seeley et al. 2007). Our results therefore speak to the idea that regions aligned with EC (outside of language processing areas) are affected by unimodal bilingualism. Specifically, it has been suggested that the role of the DLPFC is in working memory, attention control (mediation of such storage and selection of relevant information [Curtis and D’Esposito 2003]), conflict resolution (Bunge et al. 2002), and inhibition (Ridderinkhof et al. 2004).

Our results also dovetail with clinical behavioral work showing that performance on a Flanker Task was associated with GMV in bilateral DLPFC in a cohort of controls and patients with various neurodegenerative diseases (Luks et al. 2010). Smaller brain volume (i.e., gray and white matter) in DLPFC has also been observed in attention-deficit hyperactivity disorder [reviewed by Seidman et al. (2005)]. However, we did not observe differences in the anterior cingulate, which is known to be involved in conflict resolution (Kerns et al. 2004), and which has been shown to be less active in fMRI studies of early bilinguals during conflict monitoring, and to contain more GMV in bilinguals than monolinguals (Abutalebi et al. 2012). In summary, GMV differences in unimodal bilinguals, but not bimodal bilinguals, reside in part in left hemisphere language areas, consistent with the notion that the presence of 2 languages affects language representation and language control (Garbin et al. 2010; Rodríguez-Pujadas et al. 2013). Most notably, however, are the extensive differences in right DLPFC and parietal cortex associated with EC (Seeley et al. 2007) and attention (Behrmann et al. 2004).

Brain anatomical findings have previously been conducive to also understanding the long-term cognitive advantages reported in elderly bilinguals. Luk and colleagues demonstrated greater

white matter integrity between the corpus callosum and the bilateral superior longitudinal and right hemisphere inferior frontal-occipital and uncinate fasciculi in elderly lifelong bilinguals relative to monolinguals (Luk et al. 2011). Greater anterior-to-posterior functional connectivity was also observed in these elderly bilinguals, demonstrating that bilingualism maintains long-range cortical connections in old age. Bilingualism has also been suggested to be a contributor to “cognitive reserve” in aging, as absence of cognitive impairment was observed in elderly lifelong bilinguals despite the presence of reduced white matter integrity relative to lifelong monolinguals (Gold et al. 2013). Similar findings have been evident in Alzheimer’s disease patients, where greater atrophy has been observed in bilinguals compared with monolinguals, both diagnosed with probable Alzheimer’s disease, despite similar cognitive function (Schweizer et al. 2012). These observations are consistent with behavioral studies on long-term benefits of bilingualism in terms of delayed decline of executive function with aging and delayed onset of symptoms of dementia and neurodegenerative disease (Bialystok et al. 2007; Craik et al. 2010) and could in part be explained by the increased GMV identified in the present study.

In conclusion, our findings add critical information to the existing literature using behavioral and anatomical studies to address the debate about the bilingual advantage theory. First, we show objective anatomical evidence for the previously observed heightened EC in adult unimodal bilinguals (Bialystok et al. 2012). Second, we probe the theoretical explanation of the bilingual advantage theory and test the postulation that differences in bilinguals are related to the need to choose between 2 languages rather than the representation of 2 languages per se (e.g., leading to greater vocabulary). These were arbitrated by the addition of a bimodal bilingual group, and the absence of GMV differences in this group, as expected based on the dual modality of their languages, supports the idea that it is the cognitive control required to manage 2 languages in unimodal bilinguals that is likely to be the reason for their EC advantage.

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