

UC Riverside

UC Riverside Previously Published Works

Title

Anterior insular thickness predicts speech sound learning ability in bilinguals

Permalink

<https://escholarship.org/uc/item/4s19t7mc>

Authors

Rodriguez, Stephen Matthew

Archila-Suerte, Pilar

Vaughn, Kelly A

et al.

Publication Date

2018

DOI

10.1016/j.neuroimage.2017.10.038

Peer reviewed



Anterior insular thickness predicts speech sound learning ability in bilinguals[☆]



Stephen Matthew Rodriguez^{a,*}, Pilar Archila-Suerte^a, Kelly A. Vaughn^a, Christine Chiarello^b, Arturo E. Hernandez^a

^a University of Houston, 4800 Calhoun Rd., Houston, TX 77004, USA

^b University of California, Riverside, 900 University Ave., Riverside, CA 92521, USA

ARTICLE INFO

Keywords:

Neuroanatomy
Speech learning
Bilingualism
Insula

ABSTRACT

A previous fMRI study of novel speech sound learning, tied to the methods and results presented here, identified groups of advanced and novice learners and related their classification to neural activity. To complement those results and better elucidate the role of the entire neural system in speech learning, the current study analyzed the neuroanatomical data with the goals of 1) uncovering the regions of interest (ROIs) that predicted speech learning performance in a sample of monolingual and bilingual adults, and 2) examining if the relationship between cortical thickness from selected ROIs and individual learning ability depends on language group. The ROIs selected were brain regions well-established in the literature as areas associated with language and speech processing (i.e., Transverse Superior Temporal Gyrus, anterior insula and posterior insula, all bilaterally). High-resolution brain scans (T1-weighted) were acquired from 23 Spanish-English bilinguals and 20 English monolingual adults. The thickness of the left anterior insula significantly predicted speech sound learning ability in bilinguals but not monolinguals. These results suggest that aptitude for learning a new language is associated with variations in the cortical thickness of the left anterior insula in bilinguals. These findings may provide insight into the higher order mechanisms involved in speech perception and advance our understanding of the unique strategies employed by the bilingual brain during language learning.

Language acquisition in humans is a tremendously complex process that involves a multitude of motor, sensory and cognitive domains (Oh et al., 2014). Therefore, it is not surprising to discover that a large variety of regions in the brain have been implicated in playing a role in language processing. A great body of evidence supports the idea of language learning involving regions far beyond the classic language centers (Broca's area and Wernicke's area), including areas in the cerebellum and basal ganglia (Booth et al., 2007). Previous research examining the neural correlates of language in the human brain has used fMRI data to identify the regions that play a role in language processing. A meta-analysis of 100 fMRI studies has identified regions associated with specific types of language processing with prelexical speech perception being linked to activity in the bilateral superior temporal gyri, semantic retrieval with activity in the left angular gyrus and pars orbitalis, as well as a number of frontal regions, including the anterior insula, associated

with sentence comprehension (Price, 2010). The intricate connectivity of these varied regions appears to be of critical importance in language processing and according to diffusion tensor imaging studies, unique to the human brain (Friederici, 2009).

Individual differences in speech learning have been observed in numerous studies (Blau et al., 2010; Gaab et al., 2006; Golestani and Zatorre, 2004; Simos et al., 2002). These studies typically classify their participants as successful or unsuccessful learners given their performance on auditory discrimination assessments. A neurofunctional study conducted by Archila-Suerte et al. (2016) and linked to the methodology and results presented here, identified 2 groups in their sample of monolingual and bilingual participants. These groups were advanced and non-advanced learners that emerged statistically after completing a phonetic training task with novel non-native speech sounds. The aforementioned study found that great variation exists in participants' ability

[☆] All authors contributed to the development of this project. Specifically, Mr. Rodriguez wrote the literature, methods, and discussion; Dr. Archila-Suerte collected and analyzed the data, provided the methodology from Archila-Suerte et al. (2016), wrote the results, and edited the manuscript. Kelly A. Vaughn assisted with statistical analyses. Dr. Chiarello provided her expertise to comment on various aspects of the manuscript, and Dr. Hernandez provided comments and funding for data collection.

* Corresponding author. Department of Psychology, University of Houston, TX 77004, USA.

E-mail address: matt23411@gmail.com (S.M. Rodriguez).

to discriminate non-native speech contrasts. To complement those neurofunctional findings, the current study examined the neuroanatomical data with the intention of 1) revealing if cortical differences in *a priori* regions of interest (ROIs) would predict speech learning performance in a sample of monolingual and bilingual adults, and 2) examining if the relationship between cortical thickness from the selected ROIs and speech learning ability depends on language group (i.e., monolingual or bilingual). The neuroanatomical ROIs selected for the present study were regions well-known to be involved in language processing (i.e., Transverse Superior Temporal Gyrus, anterior insula and posterior insula, all bilaterally).

The selected regions of interest were hypothesized to be especially relevant in the learning of novel speech sounds due to their involvement with both primary auditory processing and potentially with higher-order processing, a function that is believed to be important in language acquisition, especially in bilinguals (Abutalebi and Green, 2007; Garbin et al., 2011). Previous fMRI research has shown insula recruitment during phonetic learning (Golestani and Zatorre, 2004) and anterior insula activation during second-language attainment (Chee et al., 2004), as well as word-deafness in posterior insula pathology (Ardila, 1999). The anterior insula has associations with a number of language related functions including phonological recognition, articulatory planning and language repetition ability (Ardila et al., 2014; Price, 2010). The insula is also uniquely positioned to serve as a potential coordinator of higher-order language processing, with direct connections to Broca's area and other language centers (Oh et al., 2014). In addition, meta-analysis of PET and fMRI studies examining expressive language tasks has found that the insular cortex may serve as a functional relay between the motor and cognitive aspects of language (Eickhoff et al., 2009). This finding further suggests that the insula may be important in speech processing and language acquisition.

In addition, the transverse temporal gyrus was examined due to the regions' many associations with primary auditory processing, including speech processing and discrimination (Formisano et al., 2008; Patterson et al., 2002; Warrier et al., 2009). Heschl's gyrus has long been implicated in speech related functions beyond primary auditory processing (Dierks et al., 1999). The region has been shown to have specific associations with speech learning ability (Wong et al., 2007) and also specifically with phonetic learning ability (Golestani et al., 2007). Furthermore, MRI data has identified differences in the morphology of the Heschl's gyrus in individuals with varying degrees of audition related training, with musically trained individuals showing thicker gray matter in this region than musically untrained individuals (Gaser, & Schlaug, 2003). An earlier study similarly identified morphological variations in Heschl's gyrus and a concomitant variation in aptitude, specifically in musicians (Schneider et al., 2002). The previous findings suggest that Heschl's gyrus may play an important role in speech processing and though definite causality is difficult to determine, structural variations in the region may be a reflection of an individual's environment. Furthermore, these structural differences may have some association with varying degrees of aptitude in auditory processing which may affect speech processing ability.

Two analyses were conducted to address each of the research goals stated above. The first analysis consisted of multiple regressions conducted to reveal which of the ROIs selected *a priori* best predicted performance of novel speech sound discrimination - based on scores obtained from a phonetic training task conducted by Archila-Suerte et al. (2016). The second analysis examined the role of individual ability and language group on the thickness of the newly found ROIs - as shown by the first analysis. That is, the second analysis examined if individual ability interacts with language group to predict thickness of such ROIs found. Positive and negative relationships between cortical thickness and performance in different linguistic tasks have been observed in numerous studies (Porter et al., 2011; Golestani et al., 2007; Bermudez et al., 2009). It has also been demonstrated that abilities of speech perception and production, specifically the pronunciation of phonetically irregular words, is associated with variations in the cortical thickness of several

brain regions, including the transverse superior temporal gyrus (Blackmon et al., 2010).

In consideration of past research associating neuroanatomical variations with increased performance on a number of tasks, it was hypothesized that cortical thickness of one or more regions of interest would predict speech sound learning ability. The selected regions (i.e., anterior insula, posterior insula, and transverse superior temporal gyrus) were hypothesized to be especially relevant to this skill due to their associations with speech-related functions, including higher-order executive functions that have been shown to be important in language learning, particularly in bilinguals. Furthermore, it was predicted that the association may be a negative relationship, as it was deemed that ability was likely to be at least partially determined by neural efficiency, a theory that has been implicated in previous fMRI studies identifying decreased cortical activity with more proficient learners (Tatsuno and Sakai, 2005; Wang et al., 2003a,b). Lastly, the examination of different language groups was predicted to reveal unique variations in the bilingual participants, a potential reflection of the varied phonological environments commonly experienced by bilinguals.

Methods

Participants

A sample of 43 English monolinguals and early Spanish-English bilinguals participated in the study. There were 20 participants in the monolingual group (12 females), and 23 participants in the bilingual group (17 females). Participants in the bilingual group learned Spanish as their first language and sequentially learned English as their second language. Overall, the age range was 18–34 years of age ($M = 22.2$, $SD = 3.3$). At the time of testing, participants had completed on average 16.7 years of education. In accordance with the Edinburgh inventory (Oldfield, 1971), all participants were right-handed. None of the participants reported history of language or speech disorders. All participants consented to the protocol approved by the Committee for the Protection of Human Subjects (CPHS) at the University of Houston. The sample of participants presented here was previously analyzed as part of a fMRI study on speech sound learning (Archila-Suerte et al., 2016).

Procedure followed in Archila-Suerte et al. (2016)

Participants visited the lab a total of six times, according to the following schedule. On day 1, participants completed background and language history questionnaires to verify eligibility for the study and the standardized Woodcock Language Proficiency Battery - Revised (Woodcock, 1995) to assess linguistic competence. On day 2, prior to initiating phonetic training, participants completed an MRI session. On days 3 thru 6, participants completed a phonetic training session each day. A five-minute posttest was given after each training session, for a total of four posttests. During the training sessions and posttests outside the scanner, participants were instructed to listen to pairs of pseudowords and determine if these were the same or different. All trials presented during training sessions and posttests contained different exemplars of the same pseudowords (e.g., different recordings from the same speakers). A button-box which contained two options, a *same* button and a *different* button, was used by participants to indicate "same" and "different" pairs. Participants were presented with randomized trials and each training session lasted approximately 25 min.

Behavioral assessments used in Archila-Suerte et al. (2016)

Online background and language history questionnaires: Demographic, academic, medical, linguistic, and socioeducational background information was collected with these surveys. Socioeducational information was collected using a 6-point Likert scale (1 = less than elementary education, 6 = advanced degree).

Woodcock language proficiency battery – Revised (WLPB-R): Overall receptive and expressive abilities in English were measured using the subtests of picture vocabulary and listening comprehension (Woodcock, 1995). An analogous assessment in Spanish, the **Woodcock-Munoz Language Proficiency Battery (1995)**, was used to verify eligibility in bilingual participants. Individuals who did not reach a minimum score of 10 items in Spanish production or comprehension were excluded from the study.

Stimuli used in Archila-Suerte et al. (2016)

Pseudowords for the phonetic training task were created using eight [8] distinct Hungarian vowel sounds. The vowel sounds selected had similar analogs in the inventories of both English and Spanish or did not exist in either language. Stimuli were recorded at the Research Institute for Linguists for the Hungarian Academy of Sciences in Budapest, Hungary, in a sound-treated room using an external audio card M-audio fast pro and an Audio Technica microphone AT 4040. Disyllabic pseudowords that were equally likely to be part of English or Spanish were used to prevent biasing the monolingual group to perform better with pseudowords that are more likely to fit their language repertoire (e.g., gyotyod – gyütyüd). The pseudowords for this study were provided by eight native Hungarian speakers (four females, four males) between the ages of 27 and 33. The speakers were instructed to read pseudowords using three different sets of instructions. During the first set of instructions, speakers were asked to carefully enunciate the pseudowords and to emphasize each vowel's characteristics. During the second set of instructions, speakers were instructed to read the pseudowords slightly faster while still carefully enunciating the words. During the third and final set of instructions, speakers were instructed to read the pseudowords at a rate that would be congruent with a regular conversation. The speakers read the pseudowords in carrier sentences to ensure that a conversational quality was obtained.

Phonetic training employed in Archila-Suerte et al. (2016)

The training task was developed using PsyScope X Build 57 (Cohen et al., 2010). High variability phonetic training (HVPT) was chosen because it is known to generalize learning from trained stimuli to untrained stimuli and to provide lasting improvements that remain for as long as six months (Iverson et al., 2005; McCandliss et al., 2002). Participants learned to discriminate vowel sounds (same vs. different) with assistance from computerized feedback, more specifically, a beep for correct responses and a buzz for incorrect responses. The speakers' rate of articulation in the stimuli recording (slow, fast but enunciated and conversational-rate) was manipulated during training in three distinct blocks. Block one contained trials that were carefully and slowly enunciated, block two contained trials that were articulated with increased speed, and block three contained trials that were articulated at the standard rate of conversation. Trials consisted of two pseudowords spoken by different speakers of the same gender. The duration of each trial was 1.5 s. The trials that presented the same pseudowords were labeled *same* and the trials that presented two different pseudowords were labeled *different*. Each pair of pseudowords was equivalent to one trial. There were 144 trials (96 trials of different and 48 trials of same) within each block of training, for a total of 432 trials. Because the goal was to observe participants' ability to *discriminate* speech sounds, more trials of *different* pseudowords were presented. The same trials were treated as fillers. The same condition was not a true experimental condition, but rather a control condition. As a control condition, fewer trials were sufficient to not let participants pick up the pattern of “yes, different”. Trials of same and different were randomized. The pretest and posttests used two shorter versions of the training task without feedback. For all pretest, training, and posttest sessions, participants entered a sound booth and were asked to determine if the pairs of pseudowords were the same or

different by pressing the corresponding button on a button box.

MRI scanning and processing

Imaging was performed at the Human Neuroimaging Laboratory of Baylor College of Medicine in the Texas Medical Center.¹ High spatial resolution 3D T1-weighted images were obtained with a 3-T magnetom TIM scanner (Siemens AG, Germany) and a 12-channel head coil. A Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence was implemented (TR = 1.2s, TE = 2.66 ms, 256 × 224 matrix, 1 mm³ isotropic voxel size).

FreeSurfer analyses

Cortical thickness was measured using FreeSurfer 5.3.0 software (<http://surfer.nmr.mgh.harvard.edu/>, Center for Biomedical Imaging, Charlestown, MA). The automatic processing stream in FreeSurfer strips the skull of each T1-weighted image using a watershed/surface deformation procedure (Ségonne et al., 2004) and corrects for motion. FreeSurfer also transforms images into Talairach space, and segments cortical tissue into cerebrospinal fluid, gray matter and white matter based on intensity gradients. A surface model with a mesh of triangles is used to display the cortex. Following reconstruction, deformable methods such as surface inflation are smoothed with a full-width-half maximum Gaussian kernel of 30 mm and averaged across participants using a spherical high-dimensional non-rigid averaging procedure to assist in aligning cortical folding patterns (Fischl and Dale, 2000; Fischl et al., 1999). This process is followed by the parcellation of the cerebral cortex into respective gyral and sulcal structures (Desikan et al., 2006; Fischl et al., 2004), as well as the generation of sulcal and curvature maps. Continuity and intensity information is used from the complete 3D MR volume in deformation and segmentation procedures to create representations of cortical thickness, calculated as the nearest distance from the gray/CSF boundary to the gray/white matter boundary at each vertex on the tessellated surface (Fischl and Dale, 2000). Anatomical parcellation nomenclature was based on the atlas developed by (Destrieux et al., 2010). Following automatic reconstruction of magnetic resonance images, participants' brain images were visually inspected in 2D using Freeview 1.0. The volume's slices were examined in the coronal, horizontal, and sagittal planes to ensure accurate surface extraction and labeling of the pial surface, white matter, and subcortical regions. When incorrect labels were identified, images were manually corrected and then reexamined following a second reconstruction.

Statistical analyses

Values of cortical thickness from 6 brain regions (i.e., transverse STG, anterior insula and posterior insula – bilaterally) were retrieved from FreeSurfer and imported into SPSS v.24. Two multiple regressions, one for each hemisphere, were conducted. Two analyses were conducted to address the two research questions of interest. In the first analysis, regressions were conducted separately for each hemisphere to isolate the influence of correlations between homologous areas. For both regressions, the continuous dependent variable of speech discrimination accuracy was entered. The thickness values of the ROIs selected were entered as predictor variables, for each hemisphere respectively. Intracranial volume (ICV) was included as a covariate to account for any variance related to brain size differences across participants. Additional covariates such as socioeducational background and English proficiency were included to control for their potential influence on learning. In the second analysis, the thickness values of the ROIs from the first analysis were treated as the dependent variables, and the values of speech

¹ The Human Neuroimaging Laboratory underwent a change in management and is now the Core for Advanced Magnetic Resonance Imaging (CAMRI).

discrimination performance, language group classification (monolingual, bilingual), and their interaction were treated as predictor variables.

Results

Participant characteristics

Monolingual and bilingual participants did not significantly differ in age ($F_{(1,41)} = 2.70, p = 0.10$), years of education ($F_{(1,41)} = 1.58, p = 0.21$), or number of years residing in the United States ($F_{(1,41)} = 0.02, p = 0.96$). However, monolingual and bilingual participants did differ in socioeducational background ($F_{(1,41)} = 15.54, p < 0.001$) and English proficiency ($F_{(1,41)} = 5.42, p = 0.02$). Within the group of bilinguals, the mean age of L2 acquisition was 4.04 ($SD = 2.4$) and percent language use of English was 72.61% and Spanish 27.39% at the time of testing (See Table 1).

Phonetic training

Performance discriminating novel speech sound contrasts in Hungarian was calculated by averaging the scores of all 4 posttests taken throughout the training. Therefore, instead of relying on one single data point of learning after training, 4 data points more reliably provided a score of mean learning. On average, the performance of monolingual participants from beginning to end increased by 9.1% and performance of bilingual participants increased by 9.2%. Therefore, monolinguals and bilinguals did not significantly differ behaviorally in the ability to discriminate novel speech sound contrasts ($F_{(1, 41)} = 0.72, p = 0.40$). Hence, individual differences, independently of language group status, better explained performance discriminating the contrasts; see Archila-Suerte et al. (2016). Across all participants, learning to discriminate novel speech sound contrasts ranged from a minimum of 55.21% accuracy (i.e., endpoint of poor performance) to a maximum of 87.33% accuracy (i.e., endpoint of good performance). The mean accuracy between each time point during training did not significantly differ between monolingual and bilingual groups, suggesting a similar rate of learning.

Surface-based morphometry

Two multiple regressions were performed to examine the role of cortical thickness of various regions of interest (See Fig. 1.) on novel speech sound learning. The first multiple regression examined the predictive effect of cortical thickness from 3 regions in the right hemisphere (transverse STG, anterior insula, and posterior insula) and 3 covariates (ICV, socioeducational background, and English proficiency) on

Table 1
Demographic and behavioral data.

	Monolingual	Bilingual	F (1, 41)	Sig.
Total N = 43	20	23	N/A	N/A
Age	23.05 (3.63)	21.43 (2.79)	2.7	0.108
Socioeducational background	4.65 (0.93)	3.00 (1.53)	17.54	0.001**
Total Years of Education	8.50 (10.92)	8.35 (9.50)	1.58	0.21
English Proficiency	81.71 (6.66)	75.91 (9.22)	5.42	0.02*
Years of Residence in US	8.50 (10.92)	8.35 (9.50)	0.002	0.96
L2 AoA	N/A	4.04 (2.04)	N/A	N/A
Years of Instruction in L2	N/A	12.13 (7.62)	N/A	N/A
Spanish Proficiency	N/A	71.03 (8.60)	N/A	N/A
Amount of L1 use	N/A	27.39 (16.15)	N/A	N/A
Amount of L2 use	N/A	72.61 (16.15)	N/A	N/A
ICV	1 549 716.72 (182 839.27)	1 518 664.90 (105 423.54)	0.48	0.49

Note: Standard deviations are in parentheses.

performance discriminating novel speech sound contrasts. None of the independent variables in the right hemisphere were found to significantly explain learning performance ($F_{(6,36)} = 0.50, p = 0.79$).

In a similar fashion, the second multiple regression examined whether cortical thickness of the 3 regions of interest in the left hemisphere and the same 3 covariates (ICV, socioeducational background, and English proficiency) would predict participants' performance discriminating novel speech sound contrasts. Here, it was found that of all the variables entered in the model, only thickness of the left anterior insula significantly explained the variability observed in learning ($F_{(6,36)} = 2.42, p = 0.04$; $t = -2.59, p = 0.01$; $R^2 = 0.28$, standard error of the estimate = 8.97; Beta/Pearson's $r = -0.43, p = 0.003$), with reduced cortical thickness of the left anterior insula predicting more successful learning and increased cortical thickness predicting less successful learning. It is worth noting that the Pearson correlation between standardized residual and predictive values was non-significant ($r = 0.00, p = 1.0$), thereby meeting the assumption of homoscedasticity (See Fig. 2).

After revealing that thickness of the anterior insula predicted performance discriminating novel speech sound contrasts in the first analysis, a second regression analysis was conducted to examine whether ability to discriminate novel speech sounds or experience with two phonological systems (or both, in an interaction) predicted cortical thickness of the anterior insula. This regression enabled us to examine the role of ability (i.e., nature) and the role of phonological experience with more than one language (i.e., nurture) on brain morphology. The results showed a significant interaction between speech sound discrimination ability and language group on anterior insular thickness in the left hemisphere ($F_{(3,39)} = 5.13, p = 0.004$; Beta = $-3.1, t = -0.20, p = 0.04$). Therefore, the results showed that cortical thickness of the left anterior insula varied with the individual's sound discrimination ability and the language background of the participant. This interaction corroborates the significant correlation initially observed in bilinguals but not in monolinguals, as mentioned above. See Fig. 3.

Discussion

The results show that better performance discriminating novel speech sound contrasts is associated with thinner cortex in the left anterior insula, a region implicated in speech processing and higher-order language related functions (Bamiou et al., 2003; Price, 2010). In addition, this association appears to be only present in the bilingual group. Learning to accurately discriminate novel speech sound contrasts is an integral part of learning language and thus proficiency in this skill may be closely associated with overall language acquisition ability. There is considerable evidence to suggest that the anterior insula is not only involved in language processing, but may be a key integrative region that participates in higher-order language functions that are important in speech processing (Oh et al., 2014). Additionally, the insula has been implicated in a specific higher-order function, the detection and integration of novel auditory stimuli (Bamiou et al., 2003), that is of critical importance in the learning of a new language. Despite previous research associating the posterior insula with phonological functions (Marshall et al., 1996), no relationship was found in our analysis.

Clinical research conducted in the early 20th century examining aphasic patients noted anterior insular involvement (Dejerine, 1914; Bernheim, 1900). Significant language deficits have been observed in patients with insular damage and lesions specifically to the left anterior insula has been found to impair speech initiation (Shuren, 1993; Dronkers, 1996). The cytoarchitectonic structure and connectivity of the insula further indicate a potential role in both language processing and higher-order functions (Bamiou et al., 2003). Previous findings have suggested that the insula is functionally segmented; the anterior portion has been shown to be involved in language articulation planning, organization, and initiation; while the more posterior segments seem to be associated with word retrieval, phonological discrimination, lexical

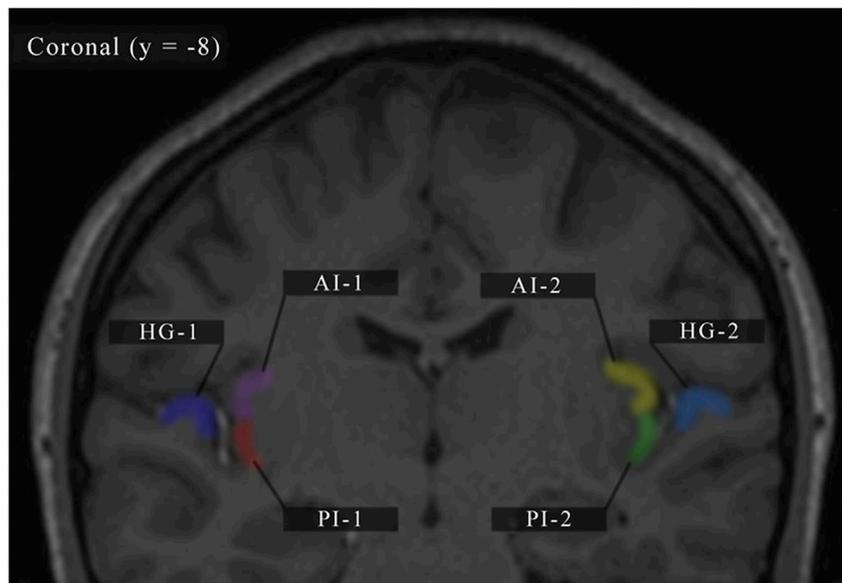


Fig. 1. Identification and labeling of the ROIs, including the right and left anterior insula (AI), posterior insula (PI) and Heschl's gyrus (HG). AI-1 = Right Anterior Insula; PI-1 = Right Posterior Insula; HG-1 = Right Heschl's gyrus; AI-2 = Left Anterior Insula; PI-2 = Left Posterior Insula; HG-2 = Left Heschl's gyrus.

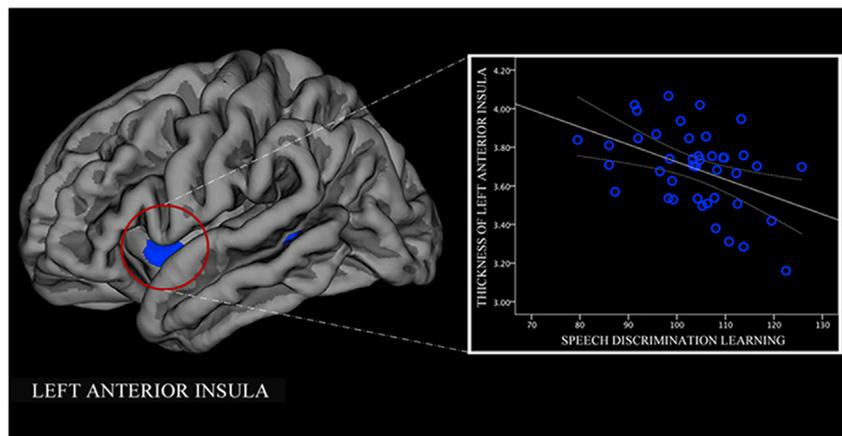


Fig. 2. An inverse relationship between cortical thickness and speech discrimination learning is found in the left anterior insula of the sample (n = 43).

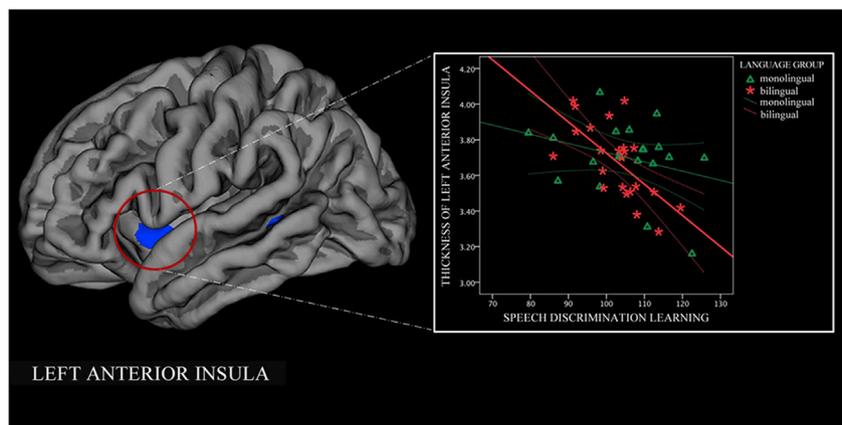


Fig. 3. Examination of cortical thickness and speech discrimination learning as a function of language group (monolingual, bilingual) revealed a significant inverse relationship between bilinguals ($r = -0.60$, $p < 0.001$) but not monolinguals ($r = -0.30$, $p = 0.19$).

knowledge, as well as general language comprehension (Ardila et al., 2014). Collectively, these findings support the notion that the insula is both anatomically and functionally ideal for integrating language related

information, as would be expected for a region presumed to assist in the complex process of speech learning. Therefore, it could be postulated that a better developed insula would result in increased speech learning

ability. The question then becomes what constitutes a “better” developed insula, as well as what neuroanatomical variations should be expected and why.

A seminal voxel-based morphometry study identifying significantly larger posterior hippocampi in London taxi drivers (Maguire et al., 2000) spurred numerous related studies that have found associations between proficiency in specific tasks and variations in select regions of the brain. Longitudinal training studies have been conducted in an attempt to eliminate potentially confounding factors such as selection. For example (Draganski et al., 2004), conducted a juggling training study during which participants' brains were imaged before and after 3 months of instruction. Skilled performers showed expansion of gray matter in bilateral mid-temporal areas and the left posterior intra-parietal sulcus, while controls showed no changes over the same period of time. A plethora of research on the subject of neuroplasticity provides support for the concept that behavior, as well as one's environment, directly affects the physical structure of the brain, which in turn affects behavior (Zatorre et al., 2012). Thus, it can be hypothesized that a reciprocal relationship also exists with speech learning and phonetic experience.

Additional research has identified changes in the gray matter volume of specific regions following training or experience (Taubert et al., 2010; Golestani et al., 2007). This finding is consistent with the current understanding of neuroplasticity and the accompanying changes associated with the process, which includes both neuronal and non-neuronal modifications that result in measurable structural changes. Experiential changes in cortical thickness have been attributed to a variety of specific processes, including neurogenesis, gliogenesis, synaptogenesis, vascular changes and neuronal morphology changes (Zatorre et al., 2012). The exact or dominant processes appear to differ depending on the specific region of the brain observed, for example, microscopic neuroplastic changes observed in rats varies between motor and visual spatial regions following learning (Kolb et al., 2008). Alternatively, an apparent shift of the gray/white matter boundary could be the result of changes in intracortical myelination, a concern raised in previous research (Glasser and Van Essen, 2011). Although the underlying neurobiology remains uncertain, collectively, prior findings indicate that variations in cortical thickness may be associated with varying degrees of proficiency in specific tasks.

The negative relation between cortical thickness and language learning ability found in our participants is in accordance with previous investigations that have shown thinner cortex relates to better performance in specific domains (Dickerson et al., 2008; Shaw et al., 2006). Extensive synaptic pruning that leads to a more efficient neural network is a potential explanation that is supported with past research (Mimura et al., 2003). Increased proficiency has been associated with decreased BOLD signals in numerous fMRI studies, ostensibly an indication of increased efficiency within the examined regions (Chee et al., 2001).

Therefore, it could be postulated that the decreased cortical thickness in the left anterior insula of the more proficient participants may be an indication of a more refined underlying neural network that allows for increased ability in learning novel speech sound contrasts. Previous longitudinal research has shown thinning of several cortical regions related to language skills during the normal development of the brain (Lu et al., 2007). The development of this region could be a result of genetic predispositions, experience-dependent changes, or a confluence of both. However, our results indicate that the relationship between left anterior insular thickness and speech learning proficiency is more pronounced in bilingual participants, a finding that may suggest experience-dependent changes are a dominant driving force in language related anterior insular development. Considering previous research describing bilingual brains as more likely to be exposed to a larger variety of phonemes (Archila-Suerte et al., 2011; Flege et al., 2003; Iverson et al., 2003), it could be postulated that this more diverse phonological environment contributed to the variations identified in our bilingual participants.

The significance of insular variations in the bilingual participants may be a result of specific neurocognitive demands that are of particular

importance in the multilingual brain, including executive control functions like switching, saliency, control, and attention. Though these functions are also involved in non-bilingual language processing, research has shown increased importance in multilingual language systems (Abutalebi, 2008). The anterior insula has been implicated in playing a significant role in many of the aforementioned tasks (Menon and Uddin, 2010). Consequently, it could be further postulated that variations in the anterior insula most significantly predicted the bilingual participants' learning performance because this region plays a role in executive control functions that are of special importance in multi-language processing.

Although several potentially confounding variables such as SES, age and years of education were controlled for in the current study, there remain additional confounding variables that may have had an effect on our results. Gender was not considered during the analysis of participants and sex has been identified as a potential factor in cortical thickness variations (Sowell et al., 2007). Further investigation into the actual cytoarchitecture of cortical regions found to have inverse relationships between thickness and proficiency, such as the insula, may be revealing and would potentially provide greater insight into the structure-function relationship that appears to exist in certain regions of the brain.

In summation, our results provide novel evidence suggesting that the thickness of the left anterior insula, a region previously implicated in speech processing, predicts phoneme discrimination ability in bilinguals but not monolinguals. Furthermore, our findings contribute to the growing body of evidence that shows thinner cortices in specific regions of the brain are associated with better performance. Lastly, our findings also provide additional evidence to support the general concept of the bilingual brain being unique both in structure and in function.

References

- Abutalebi, J., 2008. Neural aspects of second language representation and language control. *Acta Psychol.* 128 (3), 466–478.
- Abutalebi, J., Green, D., 2007. Bilingual language production: the neurocognition of language representation and control. *J. Neurolinguistics* 20 (3), 242–275.
- Archila-Suerte, P., Bunta, F., Hernandez, A.E., 2016. Speech sound learning depends on individuals' ability, not just experience. *Int. J. Biling.* 20 (3), 231–253.
- Archila-Suerte, P., Zevin, J., Bunta, F., Hernandez, A.E., 2011. Age of acquisition and proficiency in a second language independently influence the perception of non-native speech. *Biling. Lang. Cognit.* 15 (1), 190–201.
- Ardila, A., 1999. The role of insula in language: an unsettled question. *Aphasiology* 13 (1), 79–87.
- Ardila, A., Bernal, B., Rosselli, M., 2014. Participation of the insula in language revisited: a meta-analytic connectivity study. *J. Neurolinguistics* 29, 31–41.
- Bamiou, D.E., Musiek, F.E., Luxon, L.M., 2003. The insula (Island of Reil) and its role in auditory processing: literature review. *Brain Res. Rev.* 42 (2), 143–154.
- Bermudez, P., Lerch, J.P., Evans, A.C., Zatorre, R.J., 2009. Neuroanatomical correlates of musicianship as revealed by cortical thickness and voxel-based morphometry. *Cereb. Cortex* 19 (7), 1583–1596.
- Bernheim, F., 1900. *De l'Aphasie Motrice*. Paris: These de Paris.
- Blackmon, K., Barr, W.B., Kuzniecky, R., DuBois, J., Carlson, C., Quinn, B.T., Devinsky, O., 2010. Phonetically irregular word pronunciation and cortical thickness in the adult brain. *Neuroimage* 51 (4), 1453–1458.
- Blau, V., Reithler, J., van Atteveldt, N., Seitz, J., Gerretsen, P., Goebel, R., Blomert, L., 2010. Deviant processing of letters and speech sounds as proximate cause of reading failure: a functional magnetic resonance imaging study of dyslexic children. *Brain* 133 (3), 868–879.
- Booth, J.R., Wood, L., Lu, D., Houk, J.C., Bitan, T., 2007. The role of the basal ganglia and cerebellum in language processing. *Brain Res.* 1133, 136–144.
- Chee, M.W., Hon, N., Lee, H.L., Soon, C.S., 2001. Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. *Neuroimage* 13 (6), 1155–1163.
- Chee, M.W., Soon, C.S., Lee, H.L., Pallier, C., 2004. Left insula activation: a marker for language attainment in bilinguals. *Proc. Natl. Acad. Sci. U. S. A.* 101 (42), 15265–15270.
- Cohen, J., Flatt, M., MacWhinney, B., Provost, J., 2010. *PsyScope X Build 57*.
- Desikan, R.S., Ségonne, F., Fischl, B., Quinn, B.T., Dickerson, B.C., Blacker, D., Albert, M.S., 2006. An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage* 31 (3), 968–980.
- Destrieux, C., Fischl, B., Dale, A., Halgren, E., 2010. Automatic parcellation of human cortical gyri and sulci using standard anatomical nomenclature. *Neuroimage* 53 (1), 1–15.
- Dejerine, J., 1914. *Sémiologie des affections du Système Nerveux*. Masson, Paris.

- Dickerson, B.C., Fenstermacher, E., Salat, D.H., Wolk, D.A., Maguire, R.P., Desikan, R., Blacker, D., 2008. Detection of cortical thickness correlates of cognitive performance: reliability across MRI scan sessions, scanners, and field strengths. *Neuroimage* 39 (1), 10–18.
- Dierks, T., Linden, D.E., Jandl, M., Formisano, E., Goebel, R., Lanfermann, H., Singer, W., 1999. Activation of Heschl's gyrus during auditory hallucinations. *Neuron* 22 (3), 615–621.
- Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., May, A., 2004. Neuroplasticity: changes in grey matter induced by training. *Nature* 427 (6972), 311–312.
- Dronkers, N.F., 1996. A new brain region for coordinating speech articulation. *Nature* 384 (6605), 159.
- Eickhoff, S.B., Heim, S., Zilles, K., Amunts, K., 2009. A systems perspective on the effective connectivity of overt speech production. *Philosophical transactions of the Royal Society of London A: mathematical. Phys. Eng. Sci.* 367 (1896), 2399–2421.
- Fischl, B., Dale, A.M., 2000. Measuring the thickness of the human cerebral cortex from magnetic resonance images. *Proc. Natl. Acad. Sci.* 97 (20), 11050–11055.
- Fischl, B., Sereno, M.I., Tootell, R.B., Dale, A.M., 1999. High-resolution intersubject averaging and a coordinate system for the cortical surface. *Hum. Brain Mapp.* 8 (4), 272–284.
- Fischl, B., Van Der Kouwe, A., Destrieux, C., Halgren, E., Ségonne, F., Salat, D.H., Busa, E., Seidman, L.J., Goldstein, J., Caviness, V., Makris, N., Rosen, B., Dale, A.M., 2004. Automatically parcellating the human cerebral cortex. *Cerebr. Cortex* 14 (1), 11–22.
- Fllege, J.E., Schirru, C., MacKay, I.R.A., 2003. Interaction between the native and second language phonetic subsystems. *Speech Commun.* 40 (4), 467–491.
- Formisano, E., De Martino, F., Bonte, M., Goebel, R., 2008. “Who” is saying “what”? brain-based decoding of human voice and speech. *Science* 322 (5903), 970–973.
- Friederici, A.D., 2009. Pathways to language: fiber tracts in the human brain. *Trends cognit. Sci.* 13 (4), 175–181.
- Gaab, N., Gaser, C., Schlaug, G., 2006. Improvement-related functional plasticity following pitch memory training. *Neuroimage* 31 (1), 255–263.
- Garbin, G., Costa, A., Sanjuan, A., Forn, C., Rodriguez-Pujadas, A., Ventura, N., Belloch, V., Hernandez, M., Avila, C., 2011. Neural bases of language switching in high and early proficient bilinguals. *Brain Lang.* 119 (3), 129–Noppeney, 135.
- Gaser, C., Schlaug, G., 2003. Brain structures differ between musicians and non-musicians. *J. Neurosci.* 23 (27), 9240–9245.
- Glasser, M.F., Van Essen, D.C., 2011. Mapping human cortical areas in vivo based on myelin content as revealed by T1- and T2-weighted MRI. *J. Neurosci.* 31 (32), 11597–11616.
- Golestani, N., Zatorre, R.J., 2004. Learning new sounds of speech: reallocation of neural substrates. *Neuroimage* 21 (2), 494–506.
- Golestani, N., Molko, N., Dehaene, S., LeBihan, D., Pallier, C., 2007. Brain structure predicts the learning of foreign speech sounds. *Cerebr. cortex* 17 (3), 575–582.
- Iverson, P., Hazan, V., Bannister, K., 2005. Phonetic training with acoustic cue manipulations: a comparison of methods for teaching English/r-/l/ to Japanese adults. *J. Acoust. Soc. Am.* 118 (5), 3267–3278.
- Iverson, P., Kuhl, P.K., Akahane-Yamada, R., Diesch, E., Tohkura, Y., Kettermann, A., Siebert, C., 2003. A perceptual interference account of acquisition difficulties for non-native phonemes. *Cognition* 87 (1), B47–B57.
- Kolb, B., Cioe, J., Comeau, W., 2008. Contrasting effects of motor and visual spatial learning tasks on dendritic arborization and spine density in rats. *Neurobiol. Learn. Mem.* 90 (2), 295–300.
- Lu, L.H., Leonard, C.M., Thompson, P.M., Kan, E., Jolley, J., Welcome, S.E., Sowell, E.R., 2007. Normal developmental changes in inferior frontal gray matter are associated with improvement in phonological processing: a longitudinal MRI analysis. *Cerebr. Cortex* 17 (5), 1092–1099.
- Maguire, E.A., Gadian, D.G., Johnsrude, I.S., Good, C.D., Ashburner, J., Frackowiak, R.S., Frith, C.D., 2000. Navigation-related structural change in the hippocampi of taxi drivers. *Proc. Natl. Acad. Sci.* 97 (8), 4398–4403.
- Marshall, R.M., Lazar, R.M., Mohr, J.P., Van Heertum, R.L., Mast, H., 1996. “Semantic” conduction aphasia from a posterior insular cortex infarction. *J. neuroimaging* 6 (3), 189–191.
- McCandliss, B.D., Fiez, J.A., Protopapas, A., Conway, M., McClelland, J.L., 2002. Success and failure in teaching the [r]-[l] contrast to Japanese adults: tests of a Hebbian model of plasticity and stabilization in spoken language perception. *Cognit., Affect. Behav. Neurosci.* 2 (2), 89–108.
- Menon, V., Uddin, L.Q., 2010. Saliency, switching, attention and control: a network model of insula function. *Brain Struct. Funct.* 214 (5–6), 655–667.
- Mimura, K., Kimoto, T., Okada, M., 2003. Synapse efficiency diverges due to synaptic pruning following overgrowth. *Phys. Rev. E* 68 (3), 031910.
- Oh, A., Duerden, E.G., Pang, E.W., 2014. The role of the insula in speech and language processing. *Brain Lang.* 135, 96–103.
- Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9 (1), 97–113.
- Patterson, R.D., Uppenkamp, S., Johnsrude, I.S., Griffiths, T.D., 2002. The processing of temporal pitch and melody information in auditory cortex. *Neuron* 36 (4), 767–776.
- Porter, J.N., Collins, P.F., Muetzel, R.L., Lim, K.O., Luciana, M., 2011. Associations between cortical thickness and verbal fluency in childhood, adolescence, and young adulthood. *Neuroimage* 55 (4), 1865–1877.
- Price, C.J., 2010. The anatomy of language: a review of 100 fMRI studies published in 2009. *Ann. N. Y. Acad. Sci.* 1191 (1), 62–88.
- Schneider, P., Scherg, M., Dosch, H.G., Specht, H.J., Gutschalk, A., Rupp, A., 2002. Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nat. Neurosci.* 5 (7), 688.
- Ségonne, F., Dale, A.M., Busa, E., Glessner, M., Salat, D., Hahn, H.K., Fischl, B., 2004. A hybrid approach to the skull stripping problem in MRI. *Neuroimage* 22 (3), 1060–1075.
- Shaw, P., Greenstein, D., Lerch, J., Clasen, L., Lenroot, R., Gogtay, N.E.E.A., Giedd, J., 2006. Intellectual ability and cortical development in children and adolescents. *Nature* 440 (7084), 676–679.
- Shuren, J., 1993. Insula and aphasia. *J. Neurol.* 240, 216–218.
- Sowell, E.R., Peterson, B.S., Kan, E., Woods, R.P., Yoshii, J., Bansal, R., Toga, A.W., 2007. Sex differences in cortical thickness mapped in 176 healthy individuals between 7 and 87 years of age. *Cerebr. cortex* 17 (7), 1550–1560.
- Simos, P.G., Breier, J.L., Fletcher, J.M., Foorman, B.R., Castillo, E.M., Papanicolaou, A.C., 2002. Brain mechanisms for reading words and pseudowords: an integrated approach. *Cerebr. Cortex* 12 (3), 297–305.
- Tatsuno, Y., Sakai, K.L., 2005. Language-related activations in the left prefrontal regions are differentially modulated by age, proficiency, and task demands. *J. Neurosci.* 25 (7), 1637–1644.
- Taubert, M., Draganski, B., Anwander, A., Müller, K., Horstmann, A., Villringer, A., Ragert, P., 2010. Dynamic properties of human brain structure: learning-related changes in cortical areas and associated fiber connections. *J. Neurosci.* 30 (35), 11670–11677.
- Wang, Y., Jongman, A., Sereno, J.A., 2003a. Acoustic and perceptual evaluation of Mandarin tone productions before and after perceptual training. *J. Acoust. Soc. Am.* 113 (2), 1033–1043.
- Wang, Y., Sereno, J.A., Jongman, A., Hirsch, J., 2003b. fMRI evidence for cortical modification during learning of Mandarin lexical tone. *J. cognit. Neurosci.* 15 (7), 1019–1027.
- Warrier, C., Wong, P., Penhune, V., Zatorre, R., Parrish, T., Abrams, D., Kraus, N., 2009. Relating structure to function: Heschl's gyrus and acoustic processing. *J. Neurosci.* 29 (1), 61–69.
- Woodcock, R.W., 1995. Woodcock Language Proficiency Battery – Revised (WLPB-r). Riverside Publishing, Camberwell, Australia.
- Woodcock, R.W., Muñoz-Sandoval, A., 1995. Woodcock-Johnson Language Proficiency Battery – Revised (Spanish). The Riverside Company, Itasca, IL.
- Wong, P.C., Warrier, C.M., Penhune, V.B., Roy, A.K., Sadehh, A., Parrish, T.B., Zatorre, R.J., 2007. Volume of left Heschl's gyrus and linguistic pitch learning. *Cerebr. cortex* 18 (4), 828–836.
- Zatorre, R.J., Fields, R.D., Johansen-Berg, H., 2012. Plasticity in gray and white: neuroimaging changes in brain structure during learning. *Nat. Neurosci.* 15 (4), 528–536.