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Short communication

Structural neural predictors of Farsi-English bilingualism

Visar Berisha[a,b], Davis Gilton[b], Leslie C. Baxter[c], Steven R. Corman[d], Chris Blais[e], Gene Brewer[e], Scott Ruston[d], B. Hunter Ball[e], Kimberly M. Wingert[e], Beate Peter[a,f], Corianne Rogalsky[a,*]

[a] Department of Speech and Hearing Science, Arizona State University, Tempe, AZ 85287, USA
[b] School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287, USA
[c] Barrow Neurological Institute and St. Joseph's Medical Center and Hospital, Phoenix, AZ 85013, USA
[d] The Hugh Downs School of Human Communication, Arizona State University, Tempe, AZ 85281, USA
[e] Department of Psychology, Arizona State University, Tempe, AZ 85287, USA
[f] Department of Communication Sciences and Disorders, Saint Louis University, Saint Louis, MO 63101, USA

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ABSTRACT

The neurobiology of bilingualism is hotly debated. The present study examines whether normalized cortical measurements can be used to reliably classify monolinguals versus bilinguals in a structural MRI dataset of Farsi-English bilinguals and English monolinguals. A decision tree classifier classified bilinguals with an average correct classification rate of 85%, and monolinguals with a rate of 71.4%. The most relevant regions for classification were the right supramarginal gyrus, left inferior temporal gyrus and left inferior frontal gyrus. Larger studies with carefully matched monolingual and bilingual samples are needed to confirm that features of these regions can reliably categorize monolingual and bilingual brains. Nonetheless, the present findings suggest that a single structural MRI scan, analyzed with measures readily available using default procedures in a free open-access software (Freesurfer), can be used to reliably predict an individual's language experience using a decision tree classifier, and that Farsi-English bilingualism implicates regions identified in previous group-level studies of bilingualism in other languages.

1. Introduction

The impact of bilingualism on the brain has been studied for over a century, yet continues to be debated (Paap, Johnson, & Sawi, 2015; Sebastian, Laird, & Kiran et al., 2001). A better understanding of the neural correlates of bilingualism would not only provide insights regarding language acquisition and neural plasticity, but also could provide neural and cognitive targets for enhancing second language learning. The focus of most existing second-language (L2) neuroimaging research has been to identify structural or functional differences in the brains of bilinguals versus monolinguals, particularly as a function of L2 acquisition age or L2 fluency (e.g. Ge et al., 2015; Garcia-Penton, Perez Fernandez, Iturria-Medina, Gillion-Dowens, & Carreiras, 2014; Kovelman, Baker, & Petitto, 2008; Klein, Mok, Chen, & Watkins et al., 2006, Klein et al., 2014; Kim, Relkin, Lee, & Hirsch, 1997; Mahendra, Plante, Magliore, Milman, & Trouard, 2003; Dehaene et al., 1997; Marian, Spivey & Hirsch, 2003). In one of the first neuroimaging studies to examine bilingualism, Kim et al. (1997) compared functional MRI results within left inferior frontal and left posterior superior temporal regions of interest during listening to L1 versus L2 in ten subjects, half late and half early bilinguals representing several L1 and L2 languages, including English, German, Spanish, French, Turkish, Korean, Chinese and Hebrew. These first fMRI case studies of bilingualism demonstrated that classic frontal and temporal left hemisphere L1 language regions were also engaged by L2, with the overlap between L1 and L2's activations greater for early bilinguals than late bilinguals. Subsequent group studies corroborated Kim et al.'s overall conclusions that regardless of the exact two languages spoken or age of L2 acquisition, L2 generally engages frontal and temporal regions activated by L1, with the degree of spatial separation or amplitude difference in L1 vs. L2 activations correlating with age of L2 acquisition and/or L2 proficiency (Perani & Abutalebi, 2005; Perani et al., 1998; Sakai, Miura, Narafu, & Muraishi, 2004; Wartenburger et al., 2003). However, findings from whole brain analyses also suggest that bilingualism versus monolingualism is associated with structural and functional differences in subcortical regions (Burgaleta, Sanjuan, Ventura-Campos, Sebastian-Galles, & Avila, 2016; Stocco & Prat, 2014), supplemental and pre-supplemental motor areas (Luk, Green, Abutalebi, & Grady, 2011; Rodriguez-Fornells et al., 2005), frontal-parietal cortex (Mechelli et al., 2004; Reiterer et al., 2011; Yokoyama et al., 2006), the cerebellum

* Corresponding author at: Department of Speech and Hearing Science, Arizona State University, P.O. Box 870102, Tempe, AZ 85287-0102, USA.
E-mail address: Corianne.rogalsky@asu.edu (C. Rogalsky).

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(Klein et al., 2006; Halsband, 2006), and right hemisphere regions (Mayima, Richards, Coe, Eichler, & Kuhl, 2016; Reiterer et al., 2011; Schlegel, Rudelson, & Tse, 2012). A wealth of electrophysiological work has also identified neural markers of bilingualism and L2 proficiency, including more native-like P600 and N400 responses to L2 morpho-syntactic and grammatical violations as a function of L2 proficiency (Frenck-Mestre, Osterhout, McLaughlin, & Foucart, 2008; Tanner, McLaughlin, Herschensohn, & Osterhout, 2013).

It has been suggested that the structural and functional neural differences between monolinguals and bilinguals may be related to differences in cognition as a result of bilingualism (Stocco & Prat, 2014), but a causative link between bilingualism and cognitive differences remains controversial (Bialystok, Craik, & Luk, 2012; cf. Paap & Greenberg, 2013). Nonetheless, there are several studies implicating the basal ganglia, particularly the caudate, with bilingualism and particularly with language switching and control (Klein, Milner, Zatorre, Meyer, & Evans, 1995; Luk et al., 2011; Price, Green, & Von Studnitz, 1999; Wang, Wang, Jiang, Wang, & Wu, 2013). Basal ganglia differences between monolinguals and bilinguals (and between low and high proficiency bilinguals) are present during language tasks (Grogan, Green, Ali, Crinion, & Price, 2009; Zou, Ding, Abutalebi, Shu, & Peng, 2012) as well as during some cognitive tasks requiring attentional control (Stocco & Prat, 2014; Grundy, Anderson, & Bialystok, 2017). Voluntary language switching in bilinguals also implicates the supplementary motor area (SMA) and pre-SMA (de Bruin et al., 2014; Luk et al., 2011), both of which also are involved in L2 fluency (Grogan et al., 2009) as well as speech production and motor planning for speech more broadly (Price, 2012; Segawa, Tourville, Beal, & Guenther, 2015).

Most previous studies of the neurobiology of bilingualism present group-level averaged results or case studies (see above). It is well-established, however, that group-level neuroimaging results alone often do not represent an individual's neural response to language; there is substantial individual variability regarding the location and extent of neural responses to language within known language areas such as Broca's area (Nieto-Castanon & Fedorenko, 2012; Rogalsky, Almeida, Sprouse, & Hickok, 2015). Thus it remains unclear what neural features would predict bilingualism in any given individual. Dehaene et al. (1997) noted that "late second language acquisition is not necessarily associated with a reproducible biological substrate." For example, Dehaene et al.'s group-level fMRI results in French-English bilinguals identified significant activations of the right hemisphere to L2, but also demonstrated that individual subjects show a great deal of variability in right-lateralization of responses to L2, ranging from none to right hemisphere dominance.

In the present study we examined an existing structural MRI dataset of Farsi-English bilinguals and English monolinguals to determine whether volumetric and curvature differences in various brain regions could be used to reliably classify monolinguals versus bilinguals. We hypothesized that a decision tree (DT) classifier will be able to discriminate between monolinguals and bilinguals using structural MRI measurements. We restrict our analysis to 32 anatomically-defined brain regions of interest that have been shown to be reliably involved in language processes by large meta-analyses (e.g. Price, 2010, 2012). DTs have previously been used to classify brain disease states (Aguilar et al., 2013); the present study is the first to use this methodology to predict cognitive-linguistic abilities from structural MRI data. We have included both gray and white matter measurements because the relative degree of gray versus white matter differences in the bilingual brain remains unclear (Garcia-Penton, Fernandez Garcia, Costello, Andoni Dunabeitia, & Carreiras, 2016), and gray and white matter measurements in a given region are not always correlated (Li, Legault, & Litcofsky, 2014). The present study also is the first to our knowledge to investigate the neurobiology of Farsi-English bilingualism. While most of the previous research suggests that the neurobiology of bilingualism is independent of the particular languages acquired (Ueno et al., 2014; Kim et al., 1997), there is recent evidence that the connectivity between language processing regions may vary across drastically different languages (e.g. tonal vs. non-tonal) (Ge et al., 2015); however, none of these studies have focused on Indo-Persian languages, and Farsi is not a tonal language. To that end, we extend the previous literature in two important ways: (1) we add to the limited existing literature regarding structural neural predictors (versus correlates or group-level features) of bilingualism; and (2) we investigate the neurobiology of bilingualism in Farsi bilinguals.

Table 1
Frequency of Freesurfer features identified during the cross-validation procedure (48 iterations). Only features that were identified at least once are listed. L = left hemisphere, R = right hemisphere, GM = gray matter, WM = white matter.

Feature	Frequency
L parstriangularis mean curvature	48
L inferiortemporal GM volume	48
R supramarginal GM volume	48
R superiortemporal GM volume	41
R supramarginal WM volume	20
R inferiortemporal GM volume	4
L inferiortemporal mean curvature	3
L inferiorparietal GM volume	3
L middletemporal mean curvature	2
R middletemporal mean curvature	2
R superiortemporal mean curvature	2
L inferiorparietal WM volume	1
L inferiortemporal WM volume	1
L superiortemporal WM volume	1
R superiortemporal WM volume	1
L parstriangularis GM volume	1
R bankssts GM volume	1
L Hippocampus volume	1
LThalamus-Proper volume	1
R Hippocampus volume	1
R Pallidum volume	1
R Thalamus-Proper volume	1
R Cerebellum-Cortex volume	1
R superiorfrontal mean curvature	1
L superiorfrontal GM volume	1

2. Results & discussion

Leave-one-out cross validation is used to evaluate the feature selection and classification methods. For feature selection, we use pairwise *t*-test comparisons of individual features between the monolingual and the bilingual groups on the training data only ($p < 0.1$). We correct for multiple testing by controlling the false discovery rate per the Benjamini-Hochberg method (Benjamini and Hochberg, 1995). The cross-validation procedure results in a different set of features and a different decision tree for each cross-validation fold; however certain features stand out (see Table 1). In the table, we show the list of the selected features, sorted by their selection frequency. In the right hemisphere, three features were selected in most cross-validation folds: the cortical volume of the supramarginal gyrus (selected 100% of the time), the white matter volume of the supramarginal gyrus (selected 41.7% of the time), and the cortical volume of the superior temporal gyrus (selected 85.4% of the time). In the left hemisphere, two features were selected for most cross-validation folds: the cortical volume of the inferior temporal gyrus (selected 100% of the time); and the mean curvature of the pars triangularis (selected 100% of the time). All other features were selected less than 4% of the time.

For the five features identified above, we also report the corresponding statistics on all the data for completeness. As before, alpha levels were adjusted according to the Benjamini-Hochberg method. In the right hemisphere, the three areas were identified as significantly larger in the bilingual group than the monolingual group: the cortical