Beyond Bilingualism: multilingual experience correlates with caudate volume

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Abstract

The multilingual brain must implement mechanisms that serve to select the appropriate language as a function of the communicative environment. Engaging these mechanisms on a regular basis appears to have consequences for brain structure and function. A number of reports have implicated the caudate nuclei as important nodes in polyglot language control processes, while others have shown the caudate nuclei to be structurally altered in bilingual populations compared to monolingual populations. However, the majority of published work focuses on the categorical differences between monolingual and bilingual individuals, and little is known about whether these findings extend to multilingual individuals who have even greater language control demands. In the present paper we present an analysis of the volume and morphology of the caudate nuclei in a group of 75 multilingual individuals speaking three or more languages. Volumetric analyses reveal a significant relationship between multilingual experience and right caudate volume, as well as a marginally-significant relationship with left caudate volume. Vertexwise analysis revealed a significant enlargement of dorsal and anterior portions of the left caudate nucleus with connectivity to executive and to executive brain regions, as a function of multilingual expertise. These results suggest that multilingual expertise might exercise a continuous impact on the brain, and that as additional languages beyond a second are acquired, the additional demands for control result in modifications to brain structures associated with language management processes.

Keywords: Caudate nucleus; putamen; basal ganglia; multilingualism; bilingualism; language; volumetry; morphometry

1. Introduction

Multilingual individuals face an ongoing challenge in managing their language system. In order to efficiently communicate, a polyglot brain must implement mechanisms that permit the selection of the appropriate phonological, lexical and syntactic set for the current communicative environment, and the inhibition of the irrelevant ones. The mechanisms that allow language selection have been subject to investigation from multiple perspectives, which have yielded influential psycholinguistic models (such as Bilingual Interactivation +, proposed by Dijkstra & Van Heuven, 2002; and the Revised Hierarchical Model, proposed by Kroll, van Hell, Tokowicz, & Green, 2010) and comprehensive neurobiological accounts (e.g. Abutalebi & Green, 2007; Green & Abutalebi, 2013).

The neural correlates of bilingualism have become a focus of scholarly attention since the appearance of reports of a "bilingual advantage" in various domains of cognitive function beyond language (Bialystok, 2011; Bialystok, Craik, & Luk, 2012; Diamond). The existence of such an advantage is disputed, and indeed effects are not always replicated (Paap & Greenberg, 2013; Paap, Johnson, & Sawi, 2014, 2015). Nevertheless it could be considered disingenuous to posit that the experience of multilingualism should have no effect on the brain (Bialystok, 2017)

As a result, the quest for the neural signature of bilingualism has flourished, and evidence from functional imaging has tended to support the view that language control and cognitive control processes depend upon similar networks. Regions associated with the executive control system, including the supplementary motor area and anterior cingulate cortex as well as the dorsal striatum are repeatedly implicated in tasks requiring language control (Abutalebi & Green, 2008; Crinion et al., 2006; Hervais-Adelman, Moser-Mercer, & Golestani, 2011; Hervais-Adelman, Moser-Mercer, Michel, & Golestani, 2015).

There is, however, little consensus as to which brain regions are structurally different in bilingual individuals compared to monolinguals, and findings are remarkably heterogeneous (García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2015; Higby, Kim, & Obler, 2013; Luk & Pliatsikas, 2015). The earliest report of a reliable difference between bilingual and monolingual populations implicated a region of the left inferior parietal lobule (Mechelli et al., 2004), which was found to exhibit a higher probability of more grey matter in bilingual than monolingual individuals. This grey matter difference showed a positive correlation with proficiency and a negative one with age of acquisition of the second language in the bilinguals. Since this report, numerous other brain areas have been shown to differ structurally between bilingual and monolingual individuals. In studies having used voxel-based morphometry (VBM), differences have been found in regions including, among others, cerebellum (e.g. Pliatsikas, Johnstone, & Marinis, 2014), left anterior temporal lobe (Abutalebi et al., 2014), anterior cingulate cortex (Abutalebi et al., 2015), left putamen (Abutalebi et al., 2013), Heschl's Gyrus (Ressel et al.), left caudate (Zou, Ding, Abutalebi, Shu, & Peng, 2012), caudate nuclei, putamen and thalamus (Burgaleta, Sanjuan, Ventura-Campos, Sebastian-Galles, & Avila, 2016). The diversity in results may arise from differences across studies in one or several out of a large number of confounding variables that also differentiate groups, other than language knowledge *per se*. These factors include immigrant status, cultural factors and socio-economic status. All of these factors have also been raised as potential confounding variables for the findings or lack thereof of a "bilingual advantage" (Bak, 2016; for a thorough overview of the controversy, see Paap et al., 2015; and rebuttals by Woumans & Duyck, 2015). To date, only one previous study has compared cortical grey matter in multilingual individuals speaking more than two languages with bilinguals (Grogan et al., 2012). This investigation showed greater grey matter density in the right posterior supramarginal gyrus in the multilingual group than the bilingual group.

In the present study, we aimed to overcome some of these potential confounds by exploring relationships between individual differences in brain structure in relation to multilingual expertise within a group of polyglot individuals, who mastered a minimum of three languages. Although the reasons for any given individual developing multilingual expertise may well be different, stemming from environmental, familial, motivational or educational factors, by focusing on an already multilingual population, systematic population-level confounds are less likely to influence findings. Furthermore, this approach allows us to explore brain structure in relation to language experience beyond bilingualism, and to reveal continuous relationships between multilingual experience and brain structure that are more easily attributable to language experience *per se* than might be provided by similar categorical comparisons between mono- and multi-lingual populations. We expected that structures most crucially implicated in the control and manipulation of multiple languages would be those most affected by multilingualism. We based our predictions on the results of a previous study of "extreme language control" (Hervais-Adelman et al., 2015), which implicated the caudate nucleus and the putamen in different cognitive levels of language control - the caudate in overarching task-level control and the putamen at a lower, more mechanical moment-to-moment, level of control. Here, we predicted that multilingual language experience beyond bilingualism, i.e. in individuals who speak 3 languages or more, would be systematically and positively related to the volumes of these two subcortical structures. It is worth noting that two previous studies (Burgaleta et al., 2016; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2016) have found that the caudate nuclei of bilinguals are relatively larger compared to those of monolinguals.

2. Methods

2.1 Participants and behavioral measures

Seventy-five individuals participated in the study (mean age: 25 years 11 months, s.d. 4 years 10 months, 42 female), all had completed or were engaged in at least tertiary education. They self-reported speaking three or more languages (range: 3-9, mean 4.37, s.d. 1.23), and were interviewed on their age of language acquisition (AoA) and proficiency levels in each of their reported languages. Weighted sums of AoA (earlier receiving higher weight) and proficiency (more proficient receiving higher weight) were calculated (cf. Hervais-Adelman, et al. 2015) across languages spoken, to yield a compound and continuous index of language experience and proficiency (hereafter referred to as 'LEXP', mean: 35.15, s.d. 8.46). LEXP can be considered an aggregate measure of multilingual experience, by accounting for the contributions age of acquisition and language proficiency in addition to the total number of languages. Data were acquired in accordance with the Declaration of Helsinki, and with approval of the research ethics committees of the Lausanne and Geneva University Hospitals. Sixty-seven of the datasets were acquired as part of a separate study (Hervais-Adelman, Moser-Mercer, Murray, & Golestani, 2017), in which no analyses of the relationship between subcortical morphology and LEXP were carried out. Of the75 participants 40 had a acquired at least one second language before six years of age, and may be considered "early bilinguals", and 35 only began acquiring their second and further languages after this age, and may be considered "late bilinguals"; these groups did not differ in terms of LEXP ($t_{(69.13)}$=0.385, *p*=.70) or age ($t_{(66.99)}$=1.03, *p*=.31).

2.2 Structural MRI

T1 MPRAGE images were acquired on the same model of scanner at two different sites, this being a Siemens 3T Trio MRI scanner, with an 8-channel head-coil (sagittal orientation, FoV: 240*256, slice thickness 1.2mm, 1mm * 1mm in-plane resolution, TR 2400ms, TE 2.98ms, Phase Encoding steps: 239, Flip angle 9°). Forty-eight participants were scanned at the Brain and Behaviour Laboratory, University of Geneva, and 27 at Lausanne University Medical Centre.

2.3 Subcortical Structure Extraction and Analysis

Subcortical structures of individual brains were extracted using FIRST (Patenaude, Smith, Kennedy, & Jenkinson, 2011), a utility supplied with FSL (Jenkinson, Beckmann, Behrens, Woolrich, & Smith, 2012). Segmentations of the left and right caudate nuclei and putamen were visually inspected for accuracy. In order to be able to account for the potential impact of head size on the volume of structures, estimated total intracranial volume (eTIV) was extracted, using the CAT12 toolbox in SPM12.

2.3.1 Volumetric Analysis

All analyses were carried out in R (R Core Team). Initially, for each selected structure, weighted stepwise regression was employed to determine which covariates (from the following: Age, Sex, Handedness, eTIV, Scanner) should be included in an analysis of the contribution of LEXP to structural volume, using the WLE package (Agostinelli & Library, 2015). For all four structures under investigation (left caudate, right caudate, left putamen, right putamen), this analysis retained Age and eTIV as significant predictors of volume. Robust regression analyses were executed using the "robust" package (Wang et al., 2014), including LEXP, Age and eTIV.

2.3.2 Shape Analysis

The structures of interest were also submitted to a vertexwise analysis, in order to explore potential systematic differences in shape in relation to LEXP. Following the standard procedure implemented in FIRST, each structure was linearly registered (using 6 degrees of freedom) to the sample-specific average surface, mapped in MNI space. For each participant, a map was generated that contained the perpendicular vertexwise displacement vector required to map each vertex onto the mean. These values were then analysed using permutation-based non-parametric testing with Randomise (Stein, Winkler, Kaiser, & Dierks, 2014), and corrected for multiple comparisons using threshold free cluster enhancement (TFCE, Smith & Nichols, 2009). The design matrix contained the factor of interest (LEXP) and covariates of Age and eTIV (those retained by weighted stepwise regression as having explanatory power for the volumes of the structures of interest).

<u>3. Results</u>

Volumetric analyses revealed significant and marginally significant positive relationships between LEXP and right ($t_{(71)}$=2.19, *p* = .032) and left caudate volumes ($t_{(71)}$ = 1.99, *p* = .050), respectively.

These results are illustrated in Figure 1. No relationship was found between putaminal volumes and LEXP (both left and right $p > .75$).

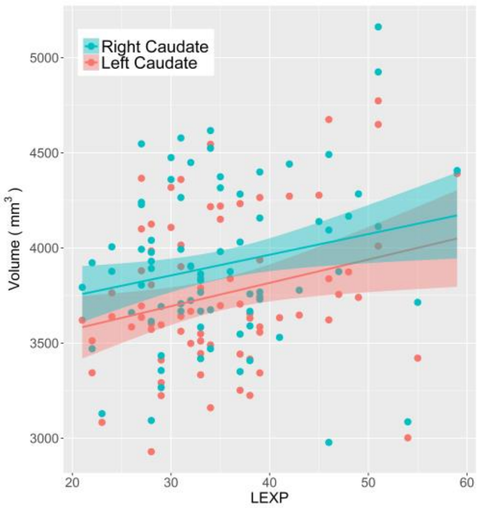

Figure 1: Scatter plot showing relationship between left and right caudate volumes and LEXP. Ribbons show 95% C.I. of robust linear regression.

Surface-based shape analysis of the structures revealed significant clusters of expansion as a function of LEXP in two distinct clusters in the left caudate nucleus, one anterior and one dorso-medial (Figure 2). The likelihood of connectivity between these two caudate clusters and other brain regions was evaluated using the probabilistic Oxford-Imanova Striatal Connectivity Atlas with 7 sub-regions supplied with FSL. The anterior cluster (centre of mass, MNI co-ordinates, mm: -12, 24, -4) was assigned 58% likelihood of connectivity to the "executive" cortex, and the dorso-medial cluster (centre of mass, MNI co-ordinates, mm: -17, 3, 25) was assigned 31% likelihood of connectivity to executive cortex and 15% to caudal motor regions.

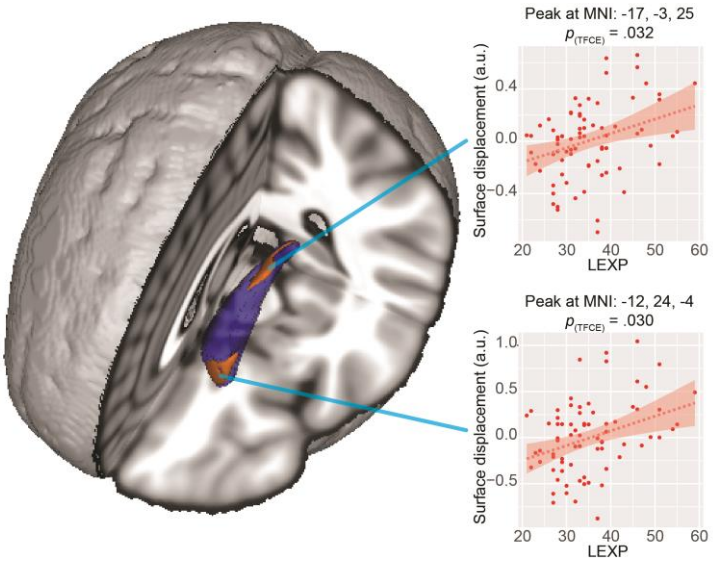

Figure 2: Rendering of standard MNI152 brain, highlighting left caudate (in blue), showing location of significant ($p_{(TFCE)} < .05$) outward surface displacement as a function of LEXP. Scatter plots illustrate displacement by LEXP at peak voxels of each indicated cluster. For illustration purposes only, trendlines show estimated robust linear regression, ribbons show 95% C.I.s for robust regression estimates.

4. Discussion

We find that increasing multilingual expertise correlates not only with bilateral caudate volume, but also with regionally-specific morphological alterations of the left caudate nucleus. These results support the view that polyglot individuals show structural adaptations that can be explained by their multilingual experience. To the best of our knowledge, this is the first demonstration of a continuous impact of increasing degrees of multilingualism on brain structure. By moving beyond the dichotomous comparison of monolingual with bilingual participants, we are able to more confidently put forward the view that the challenges of acquiring, maintaining and deploying multiple languages result in structural adaptation of the caudate nuclei. Naturally, due to the correlational nature of these analyses, the converse may be true - that individuals with relatively larger caudate nuclei are predisposed to learn and master a larger number of languages. In an effort to shed some light on the possible causality in the relationship between caudate volume and LEXP, a follow-up analysis was carried out in which the impact of early vs late bilingualism was tested, by running the robust regressions with an additional term coding for the interaction of LEXP with a categorical factor of Early vs Late bilingualism. These revealed no main effect of Early vs Late bilingualism, and no interaction with LEXP. If larger caudate volumes were predictive of a propensity to acquire more languages voluntarily, we might expect an interaction such that the relationship between LEXP and caudate volume would be stronger in the late than in the early group, since late multilinguals are more likely to have learned subsequent languages by choice, or electively. Although conclusions may not be drawn from the absence of an effect, the present data provide no evidence that larger caudate volumes tend to co-occur with later acquisition of multiple languages.

The caudate nuclei have been shown to play a role in both language control (Crinion et al., 2006; Hervais-Adelman et al., 2015) and cognitive control (Grahn, Parkinson, & Owen, 2008), and have previously been shown to be enlarged in bilinguals vs. monolinguals (Burgaleta et al., 2016; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2016). Although there is also evidence for a role of the putamen in multilingual control, it may be that the absence of an observed relationship between putaminal structure and LEXP is due to the nature of its role: if, as suggested by Hervais-Adelman and colleagues (2015), the caudate is implicated in managing lexico-semantic sets as a function of task demands (c.f. the adaptive control hypothesis Green & Abutalebi) while the putamen is involved in moment-to-moment suppression enabling the use of the appropriate language, it is conceivable that the number of competing languages does not substantially change the demands on this lower level of control.

It is, of course, essential to note that these results are found in a group of individuals who are pre-selected for a relatively unusually-high interest in languages, and that, as mentioned above, our analyses do not permit the evaluation of the causal links between the structural variation and multilingualism. Moreover, we cannot, based on the limited LEXP metric, distinguish between any potentially differential impact of proficiency, age of acquisition, factors relating to the process of acquiring, maintaining or storing multiple languages, or of more dynamic factors such as the context of language use and switching. Future work should strive to resolve this by acquiring more accurate data on these factors in polyglot populations. Nonetheless, the present study represents an important step in showing a continuous impact of language experience on a brain structure that may well be a candidate for mediating behaviours associated with the bilingual advantage.

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