



Subcortical restructuring as a function of multilingualism: Insights from monolinguals, bilinguals, trilinguals and quadrilinguals

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Abstract

Subcortical structures implicated in language control and processing adapt structurally with increasing language experience. However, the adaptation patterns across different subcortical structures remain unclear. Previous findings from bilinguals and multilinguals reveal renormalisation patterns, lending support to the Dynamic Restructuring Model (Pliatsikas, 2020). These patterns are composed of increasing volumes during the initial stages of language learning, and subsequent reductions as experience increases. T1-weighted images from 14 English monolinguals, 14 bilinguals, 14 trilinguals, and 14 quadrilinguals were obtained. The volumes of five subcortical regions implicated in language control and processing were compared amongst the groups. The findings showed group differences for every structure – caudate nucleus, nucleus accumbens, putamen, globus pallidus and thalamus. Complex patterns were unveiled for each structure, suggesting expansions and renormalisations that differ in trajectory for each group. These findings highlight the dynamic progression of subcortical adaptations, and support the notion of structural renormalisation as language experience grows.

1. Introduction

The human brain goes through structural and functional changes throughout our lifetime; not merely through maturation in development, atrophy in disease and old age, but also through adaptations in day-to-day immersive experiences and skill acquisition (Spear, 2013). The shapes and forms of neuroplasticity have been documented for a range of cognitively challenging tasks where the brain adapts to new experiences and demands. These tasks include meditation, music training, video-gaming, navigational training, and literacy among others, where grey matter regions and white matter tracts relevant for the tasks undergo adaptations (Brilliant et al., 2019; Olszewska et al., 2021; Resende et al., 2018; Saleem & Samudrala, 2017). The use of an additional language is akin to honing a cognitively challenging skill associated with the acquisition, processing, and control of multiple languages. As the languages of a bilingual are constantly and simultaneously activated, a competition in both comprehending and producing language is introduced (Green, 1998; Kroll et al., 2014; Marian & Spivey, 2003). Language control is needed to accurately monitor one's language environments and to suppress the interfering language at a moment's notice (Bialystok, 2007). Notably, the brain regions involved in language control overlap with those involved in tasks of domain-general cognitive control (e.g., De Baene et al., 2015). In dealing with such cognitive demands, the bilingual brain reorganizes itself structurally and functionally to effectively resolve this conflict, thus better facilitating successful communication (Bialystok et al., 2012; Pliatsikas, 2019).

Several studies have reported a relationship between behaviour and brain structure and function (Segall et al., 2012). However, this has not been consistently documented, as some replication studies failed to find previously reported associations (Masouleh et al., 2019). Nevertheless, studies on neuroplasticity have shown that structural changes may accompany acquisition and/or application of expert behaviours or specialised abilities (Gerber et al., 2014; Hänggi et al., 2010). The evidence includes findings from research on the use of more than one language, which demonstrates a form of specialised ability. However, a large portion of the research documenting structural adaptations was conducted by comparing monolinguals with bilinguals (e.g., García-Pentón et al., 2014; Hayakawa & Marian, 2019). Hence, the effects of being multilingual on brain structure is far less explored and little is known about how the brain modifies itself in order to acquire and handle more than two

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languages. Monolinguals, bilinguals and multilinguals differ in their language switching demands because of the number of languages they have command over. With a command of a further language, multilinguals can be said to undergo a higher level of conflict as they have more language systems simultaneously activated, from which they must select the appropriate one as quickly as a bilingual would (see Aparicio & Lavaur, 2014; Lemhöfer et al., 2004; Rothman et al., 2019). In what follows is firstly a short review of the evidence on structural adaptations stemming from bilingualism before proceeding to an overview of the adaptations relating to multilingualism, which is the focus of this study.

1.1. Bilingualism and brain adaptations

The reported patterns of adaptation differ across bilinguals, depending on the degree of language experience. With monolinguals as a baseline, the structural adaptations that appear to characterize bilinguals in the early stages of learning a non-native language are structural expansions in several cortical regions known to underlie executive functions and language processing. These regions include the supramarginal gyrus (SMG) which is involved in novel word learning, the superior temporal gyrus (STG) involved in phonological processing, the inferior parietal lobule (IPL) and inferior frontal gyrus (IFG) which are involved in the articulatory network, as well as the middle frontal gyrus (MFG), anterior cingulate cortex (ACC) and superior parietal lobule (SPL) which underlie language switching and control (Della Rosa et al., 2013; Heim et al., 2019; Klein et al., 2014; Legault et al., 2019; Mårtensson et al., 2012; Pliatsikas et al., 2020a). The expansions of these cortical regions are usually interpreted as a response to the rapidly growing vocabulary occurring at this stage of bilingualism. Bilinguals who have more language experience or have been immersed in an environment of their second language exhibit a different pattern of restructuring. This involves more effects in white matter and in subcortical grey matter structures. For instance, simultaneous bilinguals as opposed to sequential bilinguals have been found to undergo mostly modifications in subcortical structures but not in cortical structures (Burgaleta et al., 2016; Pliatsikas et al., 2017). Subcortical effects in the form of larger volumes in the caudate nucleus, putamen, globus pallidus, and thalamus have been observed in bilinguals when compared with monolinguals (Burgaleta et al., 2016; Pliatsikas et al., 2017). When compared with monolinguals or bilinguals with limited language experiences, bilinguals with higher language immersion have presented with a lack of cortical effects, and/or with contractions in the caudate nucleus, nucleus accumbens and thalamus (Costumero et al., 2020; DeLuca et al., 2019a; Korenar et al., 2023; Pliatsikas et al., 2017). In conjunction with subcortical effects, there has been corroborating evidence from studies on white matter effects in bilingual adults and children (for a review see Li et al., 2014).

1.2. Basal ganglia and language processing and control

The prominence of subcortical effects as language experience increases is not surprising, given the relevance of the basal ganglia and thalamus in language processing and control (Jacquemot & Bachoud-Lévi, 2021; Murdoch, 2009; Tomasi & Volkow, 2012). Several models such as the *Adaptive Control Hypothesis* (ACH; Green & Abutalebi, 2013) have also implicated that subcortical areas such as the caudate nucleus, putamen and thalamus are

important for language switching. For example, subcortical structures have functions relevant to language learning, speech articulation, and bilingual language processing, and clinical studies have also found that lesions to the thalamus and basal ganglia lead to language disorders (e.g., Fabbro et al., 2002). The basal ganglia, which include the nucleus accumbens, putamen, caudate nucleus and globus pallidus, play an essential part in action selection, which is a function that filters relevant information from competing but non-target information coming from the cortex. This is a crucial function in bilingual processing since being bilingual creates a state of conflict between two languages that necessitates the inhibition of the non-target language in favour of the relevant language at any one time. The caudate nucleus, a deep brain structure that also forms part of the language control network (Green & Abutalebi, 2013), has been found to be involved in executive control (inhibiting and selecting from competing action plans (Green & Kroll, 2019)), cognitive flexibility, expertise behaviours, procedural learning, fluency and articulatory control (Crinion et al., 2006; Green & Abutalebi, 2013; Hervais-Adelman et al., 2018; Janacek et al., 2020; Prasad, 2020; Verstynen et al., 2012; Wang et al., 2019). Like the caudate nucleus, the putamen and globus pallidus have motor functions involved in learning complex procedural skills and managing movements (Gooijers et al., 2016). More importantly, the putamen and globus pallidus are frequently involved in language processing pathways and have both been suggested to be involved in speech articulatory processes where damage results in poor speech production fluidity (Abutalebi et al., 2013; Burgaleta et al., 2016; Liu et al., 2010; Nadeau & Crosson, 1997; Viñas-Guasch & Wu, 2017). The nucleus accumbens is a small structure whose proximity to the caudate nucleus may have obscured its contribution to language functions in past studies (Burgaleta et al., 2016). While the thalamus is not part of the basal ganglia, it is a sizeable subcortical structure that subserves language functions (Klostermann et al., 2013). More specifically, it is implicated in the monitoring of cortical activities relating to language functions such as language selection and programming of motor routines relating to articulatory processes (Abutalebi & Green, 2016; Murdoch, 2009). It is also active in differentiating speech sounds (Alain et al., 2005). Since it appears that cortical effects occur in various bilingual populations while white matter and subcortical effects become more apparent as language experience increases, the functions of language processing and control subserved by these subcortical structures are expected to be more taxed in multilinguals than in bilinguals.

1.3. Multilingualism and brain adaptations

A very limited number of studies on structural adaptations have been conducted on multilinguals. Even though cortical effects have also been found amongst multilinguals who are representatives of greater language experience (e.g., Grogan et al., 2012; Midrigan-Ciochina et al., 2023), subcortical effects do appear to be more frequently reported in this population. For instance, when compared with Italian monolinguals, trilinguals exhibited greater grey matter density in the left putamen (Abutalebi et al., 2013), which is a structure that underlies articulatory processes (Abutalebi & Green, 2016). In a separate study on 75 individuals who used at least three languages, the volume of the bilateral caudate nucleus correlated positively with multilingual experience (Hervais-Adelman et al., 2018). Crucially, while caudate nucleus volume increased with both earlier AoA and higher proficiency, language proficiency correlated more strongly with caudate

nucleus volume than AoA. With its association with cognitive control, language switching, and lexico-semantic systems (Bradley et al., 2013), the continual adaptation of the caudate nucleus underscores its sensitivity to increasing linguistic expertise. This finding is coherent with other studies that have highlighted the role of the caudate nucleus in expertise-related behaviours (e.g., Adamson et al., 2014). This pattern of results also reflects a similar trend with Pliatsikas et al.'s (2017) immersed sequential bilinguals where reshaping of the caudate nucleus occurred for proficient bilinguals despite not using their languages continuously. The left caudate nucleus has also previously been identified as having connectivity with brain regions essential for executive control, highlighting its involvement in language monitoring and control (Abutalebi et al., 2008; Brovelli et al., 2011; Zou et al., 2012).

As language experience increases, not only do the effects shift from cortical to subcortical structures, but the effects also include DECREASES in volumes rather than increases. Individuals who have considerably greater language experience include simultaneous interpreters (SIs) who can switch between languages in real time at much higher frequencies and intensities than the typical bilingual or multilingual. Indeed, instead of cortical expansions that characterise the restructuring trajectories in less experienced bilinguals, a handful of studies comparing SIs to multilingual controls have identified volumetric contractions for the former group (Elmer et al., 2014). Crucially, the demanding task of language control that SIs are capable of has been found to facilitate structural adaptations in areas known to be involved in language control and processing. More specifically, when compared with regular multilingual controls, SIs exhibited SMALLER volumes in cortical structures such as the anterior cingulate gyrus and left SMG. Furthermore, the volume of the caudate nucleus decreased with increasing hours spent simultaneous interpreting (Elmer et al., 2014). While the inverse relationship between volume and language control ability may appear to be counterintuitive, the smaller volumes in this context are reflective of optimised brain circuits through the removal of inefficient connections. This stems from general models of synaptic pruning (Feinberg, 1982), which will be explained in further detail in the following paragraphs.

1.4. Theoretical approaches

The multilingualism effects highlighted in the small pool of studies above reflect the involvement of subcortical structures in executive control, language control and language processing, as well as the fluctuations in the volumes of the same structures among groups with different language experience. It seems that the demands of controlling and switching amongst languages are associated with structural adaptations, and these structural adaptations begin with cortical modifications that are replaced with white matter and subcortical effects as language experience increases. Several models and hypotheses have attempted to combine and interpret these findings in the literature.

A crucial theoretical approach that brings together and expounds on the interaction between structural neuroplasticity and language experience beyond two languages is the DYNAMIC RESTRUCTURING MODEL (DRM; Pliatsikas, 2020). It posits that neuroanatomical adaptations are not static; they progress and regress depending on the extent of language experiences. Furthermore, increasing language experiences are associated with

more white matter and subcortical effects rather than cortical adaptations. At the INITIAL EXPOSURE stage, exposure to a new language leads to expansions in cortical structures like the IFG, ACC, inferior parietal lobule (IPL), superior parietal lobule (SPL), and in some cases subcortical structures like the caudate nucleus. These expansions reflect the growth of neural circuits to adapt to an expanding vocabulary and the early demands of controlling between lexical alternatives. With further language experience, a bilingual arrives at the CONSOLIDATION stage where the demands revolve around controlling between the available semantic, phonological, and grammatical alternatives. At this stage, cortical structures are expected to revert to baseline volumes while greater structural connectivity of several white matter tracts and subcortical effects (mostly expansions) in structures like the caudate nucleus, putamen and thalamus begin to emerge. Finally, highly experienced bilinguals/multilinguals may arrive at PEAK EFFICIENCY: a stage centred on automated language control and characterized by stabilised or reduced subcortical volumes and greater WM diffusivity in anterior regions and lower diffusivity (i.e., indicator of more efficient structural connectivity) in posterior regions as reliance shifts from a more effortful (undertaken by frontal networks) to a more automated approach (undertaken by posterior and subcortical networks). At this stage, the underutilised neural circuits are pruned away to leave behind only the most efficient connections. This is based on general models of synaptic pruning which posit that the selective elimination of synapses optimises neural networks (Feinberg, 1982; Navlakha et al., 2015; Wenger et al., 2017). The latter two stages of the DRM are of particular relevance to the present study. The DRM is complemented by the BILINGUAL ANTERIOR TO POSTERIOR AND SUBCORTICAL SHIFT MODEL (BAPSS; Grundy et al., 2017), which posits that as bilinguals become more experienced in their second language, the site of language control shifts from frontal control regions to posterior and subcortical regions (e.g., basal ganglia and thalamus) that are typically more involved in perceptual and motor processes. This might suggest a more automated and efficient approach to cognitive control as one attains greater mastery over one's languages.

As already mentioned, these theoretical approaches could be used to explain the varied findings in the literature. For example, they could explain why the multilinguals in the small pool of available studies revealed more subcortical effects rather than cortical effects. The most striking observation about the subcortical adaptations among individuals with greater language experience is the pattern of volumetric contractions instead of expansions. The trajectory of restructuring observed in the available evidence appears to portray volumetric expansions at the initial stages of learning a new language followed by reductions towards baseline volumes as this language skill increases, reflecting renormalisation (DeLuca et al., 2019a; Elmer et al., 2014). Such findings are in line with predictions made by the DRM. For instance, with more experiences in switching between languages, multilinguals and simultaneous interpreters could be at the stages of CONSOLIDATION and/or PEAK EFFICIENCY in the DRM. At these advanced stages, the mechanisms responsible for lexical learning and control may have been streamlined and optimised, and the brain is now focused on a different task – regulating competing semantic, phonological, and grammatical options. This task is managed by the cerebellum and subcortical structures like the basal ganglia and the thalamus which are important in cognitive control. Therefore, the shift in focus as language experience increases could explain the volumetric REDUCTIONS in multiple subcortical structures.

1.5. This study

Most of the above-described theoretical approaches stem from evidence from bilinguals and a small pool of evidence from multilinguals. It is not clear whether an increasing number of spoken languages would make a difference in the predicted adaptations. To the best of our knowledge, no study has conducted a comparison of subcortical volumes amongst monolinguals, bilinguals, trilinguals and quadrilinguals. Although knowing a greater number of languages may not be fully representative of higher language experience or language control ability, all languages of a bi-/multilingual are concurrently activated and contend for selection (Lemhöfer *et al.*, 2004; Marian *et al.*, 2013; Poarch & Van Hell, 2014). Hence, being multilingual (i.e., knowing three languages or more) would at least mean having additional competitor words for the same concept, if not also multiple competing phonological and grammatical systems; this situation would be expected to require more language control than being bilingual (i.e., knowing two languages) (Schroeder & Marian, 2017), as it is, in itself, a different and more challenging linguistic experience than bilingualism, especially in immersive multilingual environments. With only a handful of studies investigating multilingualism and structural adaptations, the available evidence remains insufficient for describing what happens to brain structure after the acquisition and use of more than two languages. This study aims to identify the patterns of subcortical structural adaptations with increasing number of spoken languages, by examining structural MRI data from experienced bilingual, trilingual and quadrilingual individuals, that were also compared to data from a functionally monolingual group. The volumes of five subcortical structures that have been documented to be important in language control and processing (thalamus and the basal ganglia: nucleus accumbens, caudate nucleus [including head and tail], globus pallidus, and putamen) were extracted and compared across the four groups. Taking subcortical volumes of monolinguals as the baseline, we expect dynamic adaptations of these subcortical structures in the form of expansions and contractions (hereon referred to as renormalisation) as the language control requirements increase with the number of languages spoken. The adaptations will depend on the number of languages used, and will differ between structures, with some renormalising with greater controlling needs compared to others.

Specifically, for the caudate nucleus, similar volumes across monolinguals, bilinguals, trilinguals and quadrilinguals were predicted. This pattern would suggest that renormalisation has occurred for the bilinguals, trilinguals and quadrilinguals. This prediction is based on past studies showing caudate nucleus adaptations occurring in earlier stages of bilingualism, as well as the repeated implication of the caudate nucleus in language and cognitive control (e.g., Luk *et al.*, 2012). These suggest that the caudate nucleus may renormalise at a very fast rate; expanding during the initial exposure to a new language (i.e., L2 learners) and quickly contracting as experience in the L2 increased (i.e., immersed bilinguals). This would align with the profiles of the experienced bilinguals, trilinguals and quadrilinguals in this study.

For the nucleus accumbens, bilinguals were predicted to have larger volumes than the other three groups, who in turn may not significantly differ from each other. This pattern would suggest that the nucleus accumbens expanded as language experience increased (represented by bilinguals), and then started renormalising with further language experience, i.e., with knowledge of more than two languages, possibly even reaching the volume of

monolinguals eventually, e.g., in quadrilinguals. However, predicting the differences between trilinguals and quadrilinguals, if any, is not straightforward due to the general scarcity of evidence and the differences in linguistic immersion between these two groups (see Methods). This prediction is based on its strong connections with frontal executive regions to deliver cognitive control and mediate the selection of appropriate behaviours (Meyer & Bucci, 2016) which are imperative in switching between languages. Furthermore, recent research has shown a non-linear relationship between the volume of the nucleus accumbens and the extent of bilingual experiences (DeLuca *et al.*, 2019a; Korenar *et al.*, 2023).

For the thalamus, we predicted that monolinguals would have significantly smaller volumes than bilinguals, trilinguals and quadrilinguals. The involvement of the thalamus in language switching has been described in the ACH, and past studies have shown an increase in thalamic volumes with high language immersion and more bilingual experiences (DeLuca *et al.*, 2019a; Korenar *et al.*, 2023). The thalamus is said to manage the ongoing selection of lexical-semantic representations (Abutalebi & Green, 2016; Wahl *et al.*, 2008), which may be required to a greater degree when there are more languages available.

Finally, for the putamen and the globus pallidus, we predicted that monolinguals would have significantly smaller volumes than bilinguals, trilinguals and quadrilinguals, whereas the three multilingual groups would not differ from each other. As both the putamen and globus pallidus play similar roles in language – control of motor processes in speech articulation, it is expected that the patterns exhibited by both will be similar. This prediction is also based on past findings showing significantly greater volume in the putamen of bilinguals and trilinguals than monolinguals (Abutalebi *et al.*, 2013). Additionally, it was predicted in the DRM that as language experience continued to grow, these structures would reach stabilised volumes unless the increased experiences of quadrilinguals triggered renormalisation processes.

2. Methods

2.1. Participants

All participants filled out a language background questionnaire that also collected their education level, age and sex. The participants were enrolled in a university degree program or were holders of a university degree at the time of data collection. In total, fifty-six participants took part in this study: 14 English monolinguals (Age: 22.14, SD = 2.03) from the UK, 14 bilinguals (Age: 20.57, SD = 0.85) and 14 trilinguals (Age: 20, SD = 0.55) from Malaysia, and 14 quadrilinguals (Age: 25.86, SD = 4.28) from the Czech Republic. They all converged on knowing English. The monolinguals were born and raised in the UK and reported minimal or no exposure to additional languages. Their LSBQ composite scores were below -3.13 (mean = -6.26, SD = 0.56), which classifies them firmly as monolinguals (Anderson *et al.*, 2018). The bilinguals acquired both English and Malay simultaneously before the age of 6. The trilinguals spoke a variety of languages but converged on English and Malay for two out of three of their languages. The average AoA of all three languages occurred before the age of 7. The quadrilinguals were native users of a Slavic language and used a variety of languages but converged on knowing both English and Czech. The bilinguals and multilinguals (trilinguals and quadrilinguals) had considerable

multi-language engagement (Years of continuous use: L2 = 16.36, SD = 4.04; L3 = 13.79, SD = 4.34; L4 = 8.5, SD = 5.95). As shown by DeLuca et al. (2019b), proficiency measures may not be as useful as experience-based measures like AoA and years of use for studies of this nature. Hence, Table 1 below and Table 2 (in the appendix) illustrate participants' measures of experience. Informed consent was obtained from all participants included in the study.

2.2. MRI data acquisition

Individual T1-weighted MR images from monolingual participants were acquired in a 3.0-Tesla Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil and Syngo software at the Centre for Integrative Neuroscience and Neurodynamics, Reading, UK. Scanning parameters used: TR = 2400ms, TE = 2.41ms, flip angle = 8°, 256 sagittal slices, 0.7mm slice thickness, resolution 0.7 x 0.7 x 0.7, acquisition matrix of 246 x 256 mm, inversion time = 1140ms.

High-resolution T1 anatomical MRI data from bilingual and trilingual participants were acquired at the Centre for Nuclear Diagnostic Imaging, Universiti Putra Malaysia using a 3.0-Tesla Siemens MAGNETOM Prisma_fit MRI scanner with a 64-channel head/neck coil and sequence parameters of TR = 2300ms, TE = 2.95ms, flip angle = 9°, 256 sagittal slices, 1.2mm slice thickness, resolution 1.2 x 1 x 1, acquisition matrix of 143 x 240 mm, inversion time = 900ms.

Quadrilingual participants were scanned at the Central European Institute of Technology, Brno, Czechia using a 3.0-Tesla Siemens MAGNETOM Prisma_fit MRI scanner with a 32-channel Head Matrix coil. T1-weighted images were obtained using these scanning parameters: TR = 2400ms, TE = 2.41ms, flip angle = 8°, 256 sagittal slices, 0.7mm slice thickness, resolution 0.7 x 0.7 x 0.7, acquisition matrix of 246 x 256 mm, inversion time = 1140ms.

2.3. MRI data pre-processing

The MRI data was pre-processed and analysed with FSL pipelines. Using the default options in the fsl_anat pipeline in FSL, a series of actions were taken, including brain extraction to expose only brain tissue for analysis, tissue segmentation into CSF, white matter and grey matter, and subcortical segmentation. Subcortical segmentation was done using FIRST (FSL's Integrated Registration and Segmentation tool; FSL6.0) embedded in the fsl_anat pipeline. The structures of interest in the study included the bilateral caudate nucleus, nucleus accumbens, globus pallidus, putamen and thalamus. Every image was manually checked to

ensure that brain extraction and subcortical segmentation were performed accurately. Three individuals (C.P., M.K., J.Y.) were responsible for verification and had all agreed that the extractions were valid. The agreement was to make sure no poor-quality images (i.e., contains artifacts or motion) or images with abnormal brain structure were used. Brain extraction should not strip away any brain tissue and should leave none to minimal skull behind. Checks on segmentation accuracy were done to make sure that the subcortical segmentation followed signal intensity boundaries.

2.4. Statistical data analysis: Subcortical volumetric analysis

The volume (mm³) of each subcortical structure was obtained using fsstats of the FSL command-line utilities by specifying the respective label number of the structures (<http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FIRST/UserGuide>). The output from FIRST that was fed into fsstats was kept in a native space, so the structural images were not registered to a standard template. To control for variability in brain sizes and the use of different scanners, the volume of each subcortical structure was divided by the subject's total brain volume. The analysed values were therefore normalised subcortical volumes, which enabled us to examine how the proportion of the structure relative to total brain volume differed between groups, even if raw or absolute volumes may not be directly comparable due to the use of different scanners. By making relative comparisons, the potential confounding effects of different scanners can be reduced. However, we are aware that this strategy may not fully account for any potential impact arising from different scanners. Thus, we have also included a negative control, in which we compared total brain volumes and the volumes of the brainstem across groups. For the subcortical structures of interest, univariate analyses with Bonferroni correction were run to compare the volumes of each hemisphere of each subcortical structure across monolinguals, bilinguals, trilinguals and quadrilinguals. Group was an independent factor, hemisphere was a repeated factor while age and sex were added as covariates.

3. Results

Total brain volume was calculated for every subject, and it was important to demonstrate that no significant differences were found across groups. Indeed, all four groups had comparable total brain volumes [$F(3, 50) = 1.68, p = 0.18$]. Additionally, as the brainstem is not known to show multilingualism-induced structural changes, its volumes were analysed to establish a negative control. As expected, brainstem volumes were consistent across groups [$F(3, 50) = 1.64, p = 0.19$]. An overview of

Table 1. Participants' language backgrounds.

Group	L1		L2		L3		L4	
	AoA	Years of use	AoA	Years of use	AoA	Years of use	AoA	Years of use
Bilingual	2.46 (1.62)	18.11 (1.67)	6.00 (3.06)	14.57 (3.11)	-	-	-	-
Trilingual	2.00 (1.41)	18 (1.36)	4.36 (1.82)	15.64 (1.69)	6.21 (3.53)	13.79 (3.33)	-	-
Quadri-lingual	0	25.86 (4.28)	7.00 (3.01)	18.86 (5.32)	12.07 (2.95)	13.79 (5.29)	17.36 (5.21)	8.50 (5.95)

significant differences between groups for the five structures of interest can be found in Table 3. Raw (mm^3) and normalised (%) mean volumes of each subcortical structure for each hemisphere are presented in Table 4 in the appendix.

The analysis showed that for the caudate nucleus, monolinguals, bilinguals and trilinguals had similar volumes, but quadrilinguals had significantly larger volumes than monolinguals only. For the nucleus accumbens, bilinguals had larger volumes than monolinguals, trilinguals and quadrilinguals who had similar volumes with one another. Additionally, the left nucleus accumbens was bigger than the right nucleus accumbens across all groups. For the putamen, bilinguals and trilinguals had similar volumes with one another that were larger than monolinguals and quadrilinguals, while monolinguals and quadrilinguals exhibited similar volumes. For the globus pallidus, the analysis showed that bilinguals and trilinguals had similar volumes that were larger than those of monolinguals and quadrilinguals. Quadrilinguals had significantly larger volumes than the monolinguals. Finally, for the thalamus, monolinguals had smaller volumes than bilinguals, trilinguals and quadrilinguals, but bilinguals had significantly larger volumes than quadrilinguals. These results are illustrated in Figure 1.

4.0. Discussion

This paper built upon the premise that the brain continuously restructures itself with varying language experience. More specifically, the aim of this study was to investigate the effect of multilingualism on five subcortical brain structures involved in language control and processing. In this paper, monolinguals, bilinguals, trilinguals and quadrilinguals, all of whom lie on a spectrum of increasing language experiences with the number of languages serving as a proxy, were compared with one another. Subcortical effects were identified in the form of larger volumes in bilinguals as compared to monolinguals for the nucleus accumbens, putamen, globus pallidus and thalamus, and smaller volumes for the nucleus accumbens, putamen, and globus pallidus with even greater language experience as represented by trilinguals and quadrilinguals. Notably, similar volumes between

monolinguals and quadrilinguals were observed for the nucleus accumbens and putamen, possibly signifying either a return to baseline volumes in quadrilinguals or that the renormalisation of these structures had not started in that group.

The first pattern of results occurred for the caudate nucleus, which showed significantly larger volumes in quadrilinguals compared to monolinguals, while exhibiting comparable volumes among monolinguals, bilinguals and trilinguals. The lack of effects in bilinguals and trilinguals when compared to monolinguals was an interesting finding that partially supports our prediction. There are two ways of interpreting this lack of effects in bilinguals; either no restructuring had occurred, or expansion followed by renormalisation occurred at a fast rate as the caudate nucleus expanded in the earlier stages of bilingualism and quickly contracted as bilingual immersion/experience continued to increase. The similar volumes observed among monolinguals, bilinguals and trilinguals align with past research on bilingualism, in which caudate nucleus effects were typically found in the early stages of acquiring a non-native language but were absent in more experienced bilinguals, such as simultaneous bilinguals. Furthermore, studies have demonstrated that populations with even greater language experience, such as simultaneous interpreters, show a decrease in caudate nucleus volumes as their interpreting hours increased (Elmer et al., 2014). The caudate nucleus may thus be the fastest subcortical structure to optimise and renormalise in volume due to its integral role in language control. This coincides with recent studies showing a pattern of expansion followed by contraction of the caudate nucleus with increasing L2 immersion (DeLuca et al., 2019a; Korenar et al., 2023; Marin-Marín et al., 2022). The authors of these studies suggested that greater automation has occurred in language monitoring and selection, allowing the caudate nucleus to return to a baseline volume. Therefore, since the bilinguals and trilinguals in this study were highly immersed and have acquired their languages before the age of 7, it is plausible that the renormalisation of the caudate nucleus occurred at earlier stages of bilingualism that could not be captured with the current group of experienced individuals. The significantly larger caudate volume found in quadrilinguals when compared with monolinguals was unpredicted, even though

Table 3. Summary of effects for each structure.

	Group	Hemisphere	Group x Hemisphere	Significant pairwise effects
Caudate nucleus	$F(3, 102) = 4.14, p = .008$	$F(1, 102) = 0.02, p = .882$	$F(3, 102) = 1.33, p = .267$	Monolinguals <* Quadrilingual ($p = .02$)
Nucleus accumbens	$F(3, 102) = 9.00, p < .001$	$F(1, 102) = 20.57, p < .001$	$F(3, 102) = 0.37, p = .777$	Monolinguals <* Bilinguals ($p < .001$) Bilinguals >* Trilinguals ($p = .007$) Bilinguals >* Quadrilinguals ($p = .023$)
Putamen	$F(3, 102) = 34.53, p < .001$	$F(1, 102) = 2.98, p = .087$	$F(3, 102) = 0.54, p = .657$	Monolinguals <* Bilinguals ($p < .001$) Monolinguals <* Trilinguals ($p < .001$) Bilinguals >* Quadrilinguals ($p < .001$) Trilinguals >* Quadrilinguals ($p < .001$)
Globus pallidus	$F(3, 102) = 34.73, p < .001$	$F(1, 102) = 0.972, p = .326$	$F(1, 102) = 0.07, p = .977$	Monolinguals <* Bilinguals ($p < .001$) Monolinguals <* Trilinguals ($p < .001$) Monolinguals <* Quadrilinguals ($p < .001$) Bilinguals >* Quadrilinguals ($p = .001$) Trilinguals >* Quadrilinguals ($p = .009$)
Thalamus	$F(3, 102) = 32.93, p < .001$	$F(1, 102) = 6.11, p = .015$	$F(3, 102) = 0.46, p = .713$	Monolinguals <* Bilinguals ($p < .001$) Monolinguals <* Trilinguals ($p < .001$) Monolinguals <* Quadrilinguals ($p < .001$) Bilinguals >* Quadrilinguals ($p = .042$)

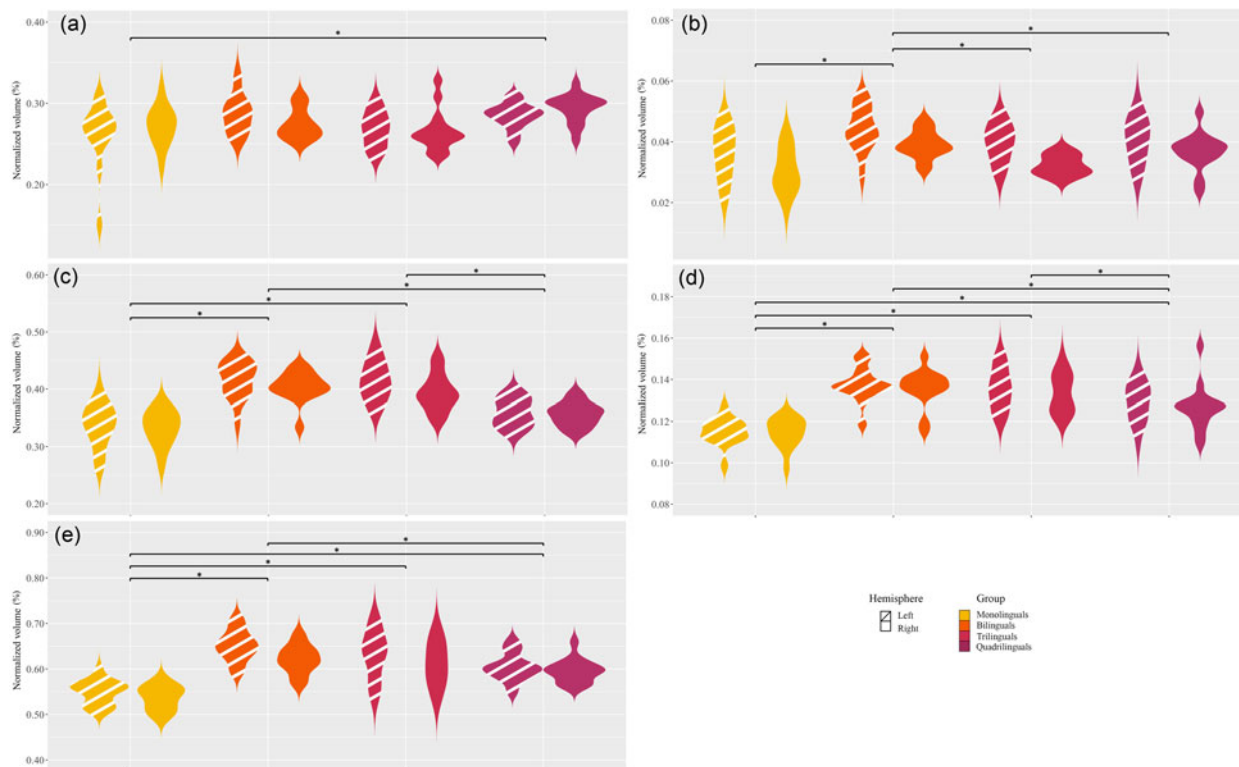


Figure 1. Normalised volumes of the a) caudate nucleus, b) nucleus accumbens, c) putamen, d) globus pallidus and e) thalamus across monolinguals, bilinguals, trilinguals, and quadrilinguals. Normalised volumes are subcortical volumes as a proportion of total brain volume (raw volume/total brain volume*100)

it is in line with a previous study conducted with multilinguals. Specifically, Hervais-Adelman et al. (2018) found a significant positive relationship between multilingualism experience and bilateral caudate volumes, which they attributed to the greater linguistic and cognitive control demands involved. Despite being able to use more languages than the other groups and reporting considerable years of continual usage of their languages, our quadrilinguals acquired their fourth languages (L4s) considerably later in life and were less immersed in a multilingual environment than the bilinguals and trilinguals. The bilinguals and trilinguals were immersed in an environment that incorporated most of their languages and enabled them to switch between their languages more extensively. In contrast, the quadrilingual group had lower immersion, as many of them knew an L4 that was not an official language in the country that they were living in. Furthermore, since the last-learned languages of the quadrilinguals were acquired later than their third languages (L3s), their years of L4 use had not caught up with their years of L3 use. It is possible that the quadrilinguals have previously optimised some of the resources for using three languages, but have yet to do so for four languages. They may be building up additional neural resources to meet the demands of using an additional language. In other words, the expansion-renormalisation pattern may restart each time new demands occur that the existing resources are unable to meet, a pattern that has already been predicted by the DRM (Pliatsikas, 2020). This interpretation would coincide with past bilingualism studies that found increment in caudate volume for low-immersion bilinguals but not immersed bilinguals (Pliatsikas et al., 2017). Perhaps, as the number of years of continuous L4 use increases, and/or with a more immersive environment, optimisation for four languages will occur and show a corresponding decrease in caudate volume.

The volume of the nucleus accumbens was found to be significantly larger in bilinguals than in monolinguals, but similar across monolinguals, trilinguals and quadrilinguals. There was also no interaction effect between hemisphere and group for the nucleus accumbens. The results suggest that renormalisation may have begun with the trilinguals and continued further with the quadrilinguals towards baseline volumes, and is in line with our predictions. Even though the nucleus accumbens is not often discussed in the context of language functions, volumetric reductions in this structure were previously found to correlate with the amount of second language immersion where greater immersion correlated with volume (DeLuca et al., 2019a). The nucleus accumbens has central roles in higher-order cognitive functions such as decision-making, action selection and learning (Abela et al., 2015), some of which have been found to be enhanced in bilinguals (see Costa et al., 2014; Hayakawa et al., 2016; Tremblay & Sabourin, 2012). More specifically, this structure facilitates the selection of rewarding stimuli by inhibiting irrelevant actions to achieve goals efficiently and remembering the outcomes of behaviours to achieve future favourable actions (Floresco, 2015). Similarly, bilinguals and multilinguals must constantly monitor conversational cues while having multiple languages activated concurrently, effectively inhibit the non-target language, and select the language appropriate for the context in order to communicate adeptly. This may imply that with increasing language experience, structural resources become streamlined to undertake the task.

A third pattern of restructuring occurred for the putamen, where bilinguals had larger volumes than monolinguals and quadrilinguals, trilinguals had larger volumes than quadrilinguals, and monolinguals and quadrilinguals had similar volumes. This is unlike our predictions of a stabilised volume for bilinguals, trilinguals and quadrilinguals. Both the globus pallidus and putamen

have general and language-specific roles such as movement regulation, orchestration of motor programs, and speech articulation which are functions integral to bilingual speech production (Fazl & Fleisher, 2018; Javed & Cascella, 2020; Koikkalainen et al., 2007; Oertel & Schulz, 2016; Syka et al., 2015; Viñas-Guasch & Wu, 2017). Knowing more than one language would expose bilinguals and multilinguals to a wider range of speech sounds and increase their verbal control needs. Furthermore, bilinguals and trilinguals in this population have been in an immersive environment where for most of them, at least two of their languages are used in their multilingual environment for both administrative and recreational purposes. Although the quadrilinguals in this study may not be immersed in an environment that actively requires all four languages, they are no doubt exposed to an even wider range of speech sounds and correspondingly greater demands for varied speech articulation. Additionally, structural adaptations of the putamen have been suggested to occur regardless of immersion, as its effects have been found in both immersed and non-immersed bilinguals (DeLuca et al., 2019a; Korenar et al., 2023; Marin-Marín et al., 2022). Therefore, the observation of smaller volumes in quadrilinguals compared to trilinguals, along with similar volumes between quadrilinguals and monolinguals, may suggest that articulatory monitoring and phonological processes have become more automatized and efficient in quadrilinguals.

The globus pallidus displayed an almost identical pattern with the putamen where bilinguals and trilinguals have significantly bigger volumes than monolinguals and quadrilinguals. A key difference is that the volume of the globus pallidus remained significantly larger in quadrilinguals when compared with monolinguals, despite a significant reduction when compared to trilinguals. Slightly similar to the results for the caudate nucleus, this suggests that while renormalisation may have begun, it has not renormalised to baseline volumes. Perhaps, with a more immersive environment, and/or the accumulation of more years of continuous L4 use, optimisation will occur and exhibit a corresponding decrease in volume to baseline for the quadrilinguals. Even though the globus pallidus shares overlapping functions with the putamen such as the coordination of motor programmes (Grillner & Robertson, 2016), it also plays a unique role in the control of lexical-semantic operations (Whelan et al., 2004). Therefore, these observed effects could reflect the ongoing process of optimising the selection of lexical-semantic alternatives by the globus pallidus. This pattern of volumetric differences is in partial support of the DRM, which predicted that as language experience increases, the volumes of the globus pallidus will remain constant. The renormalisation of the globus pallidus and putamen appears to have occurred with more language experience than the renormalisation of the caudate nucleus and nucleus accumbens. This suggests that mechanisms of language control may be optimised earlier than mechanisms relating to the execution of language such as articulation and other linguistic motor programs.

The final pattern of restructuring and one which is interpreted as the slowest rate of renormalisation occurred for the thalamus where monolinguals exhibited significantly smaller volumes than all other groups. The thalamus has not only been proposed to be involved in language switching by the ACH, but has also been implicated in many language functions, such as language selection, production, speech monitoring, semantic processing, and highlighted in past research to adapt both structurally and functionally (Burgaleta et al., 2016; Pliatsikas et al., 2017; Raji et al., 2020). In particular, it plays roles in selecting relevant lexical

and semantic representations. Thus, with increased language experiences in the form of acquiring a larger number of languages, it is believed that a larger demand would be exerted on the selection mechanisms helmed by the thalamus. It is the only subcortical structure in this study that did not exhibit similar volumes between monolinguals and trilinguals or quadrilinguals, or even a volumetric reduction from trilinguals to quadrilinguals (i.e., no renormalisation). This could be due to the thalamus playing a range of major roles not limited to language systems and motor control (Hwang et al., 2021). For example, it is involved in memory, sleep and consciousness, and is implicated in every sensory system (Bast et al., 2021; Ward, 2013). Furthermore, it is a large structure that acts as a relay hub with extensive projections and functions linked to various regions of the brain (Hwang et al., 2021). Therefore, a further increase in language experience may not be enough to trigger the restructuring of the whole structure, or the approach of this study does not have the sensitivity to detect any reshaping that may have occurred.

4.1. Theoretical implications

The findings of this study have provided insights from a multilingual population by comparing across a spectrum of individuals ranging additively from monolinguals to quadrilinguals. At a broad level, the results indicate that brain tissue can expand and contract not only through motor skill learning but also with increasing language skills. The effects found in the caudate nucleus, putamen, and thalamus echo predictions from the ACH and BAPSS where adaptations shift towards a subcortical recruitment strategy, suggesting that language switching could be less effortful and more automated with more experience. Specifically, the bigger subcortical volumes observed in bilinguals compared to monolinguals align with the BAPSS, which suggests that as L2 experience increases, reliance on subcortical structures would also increase.

Notably, these findings validate predictions from the DRM, where subcortical effects emerge with increased language experience (i.e., knowing more languages), and the observed patterns of adaptations are characterised by expansions followed by contractions back to baseline volumes. With monolinguals representing baseline volumes, knowing two languages appears to be associated with larger volumes. As a third language was “added”, the brain did not go on to “expand”. Rather, the subcortical volumes of trilinguals were either comparable to bilinguals (i.e., caudate nucleus, putamen and globus pallidus), or were significantly smaller (i.e., nucleus accumbens). Finally, with the addition of a fourth language, structures that did not “return” to baseline volumes in the trilinguals (putamen and globus pallidus) exhibited significantly smaller volumes in the quadrilinguals such that they were either matched with or closer to monolingual volumes, except for the thalamus which nevertheless showed a downward trend. The bilingual group consists of immersed bilinguals who could be said to be at the CONSOLIDATION stage of the DRM where expansions in the putamen, globus pallidus and thalamus were expected in comparison to monolinguals. The trilinguals could be between the CONSOLIDATION and PEAK EFFICIENCY stages as seen through the persistent effects in the putamen, globus pallidus, and thalamus. Pliatsikas (2020) did acknowledge that the patterns for the last stage of the DRM would be tricky to predict due to the lack of evidence from multilingual populations. These findings could therefore add to the scarce amount of evidence from populations with more language experience,

potentially informing the DRM by providing evidence of smaller volumes in the nucleus accumbens, putamen and globus pallidus with the knowledge of a third and fourth language.

The idiosyncratic pattern seen in the quadrilinguals merits special focus. Specifically, the subcortical volumes of interest were relatively bigger for quadrilinguals than trilinguals for some structures but not others, making quadrilinguals challenging to place in the context of the DRM. The unique findings for quadrilinguals may be attributed to them not being immersed in an environment that allowed them to actively use all four of their languages. Despite having fewer opportunities to switch between languages, the quadrilinguals do have the ability to use more languages than other groups, which would mean having to inhibit more languages than the others at any point in time, regardless of use, and this is a function subserved by the nucleus accumbens. The neural resources for doing so may have thus been optimised, resulting in renormalised volumes in quadrilinguals. Moreover, quadrilinguals, as discussed earlier, were undoubtedly exposed to more diverse speech sounds and had to coordinate between numerous articulatory motor programs than the other groups, which could account for the renormalised volumes of the putamen. Among its many functions, the globus pallidus shares the role of coordinating motor programs with the putamen, which could explain its decreasing volume in quadrilinguals, albeit not renormalising to baseline volumes. Conversely, while the nucleus accumbens and putamen showed smaller volumes in quadrilinguals, the caudate nucleus, globus pallidus and thalamus did not. The latter three structures share a common function – language control. Specifically, they subserve the switching between lexico-semantic representations, which may have been less available to the less-immersed quadrilinguals. Consequently, optimisation and automatization of these structures for this function may not have occurred, which could explain the sustained large volumes of these structures in quadrilinguals. In other words, higher multilingual immersion may exert unique demands on different structures.

4.2. Limitations

The current study explored the relations between subcortical restructuring and increasing number of languages, which may have neglected nuances of the bilingual and multilingual experience. Future studies could consider investigating structural adaptations with a better quantification of bilingualism and multilingualism by considering the influence of language background factors such as language proficiencies, AoA, and degree of immersion through the use of a questionnaire such as the LEAP-Q (Marian et al., 2007). Even though this study has a relatively small sample size, which future replication studies could consider addressing, we were able to make a comparison across four populations that lie on a spectrum of increasing language experience that has not been conducted before. Future studies could also compare between multilinguals (bilinguals, trilinguals and quadrilinguals) and simultaneous interpreters, who have been argued to have high levels of language control, to investigate the influence of language experience on volumetric differences in subcortical structures. Studies could also aim to investigate neuroplasticity in immersed quadrilinguals who not only possess the ability to use four languages, but also live in environments that allow them to actively use all their languages, albeit a challenge to find and recruit such participants.

Analysing MRI data collected from different sites is becoming a common practice (Grazioplene et al., 2015; Hervais-Adelman

et al., 2018), and so is the challenge of mitigating its potential effects. We acknowledge that the use of different scanners/protocols may have had unclear effects like variations in image acquisition that may consequently influence the probabilistic assignment to various tissue types or structures of interest during segmentation. In order to mitigate this potential impact, we employed FIRST and a volumetric analysis, which relied on images in a native space, instead of methods that average and register images to a standard template (e.g., voxel-based morphometry (VBM)). The full pipeline of subcortical segmentation using FIRST was run, including an inverse transformation to take it back into the native space, enabling the subsequent segmentation process to occur in the native space (Patenaude et al., 2011). In so doing, we were able to be maintain sensitivity to volumetric differences between participants and avoid other potential inaccuracies introduced by VBM. Secondly, we compared normalised subcortical volumes (raw volume/total brain volume) instead of raw volumes, which can reduce confounding effects of scanner-related variations. By doing so, we made relative comparisons, where we examined how the proportion of the structure relative to total brain volume differed between groups, even if raw/absolute volumes may not be directly comparable. However, we are aware that normalisation may not fully account for variations in scanning protocols. Hence, we further included two negative controls in the form of brainstem volumes and total brain volumes. We chose the brainstem as it not only required the same segmentation processes as the five subcortical structures of interest, but crucially, it is not known to undergo structural adaptations induced by bi-/multilingualism. Hence, any differences in brainstem volumes across groups could be attributed to systematic differences arising from scanner variation. However, no significant group differences were found, verifying the absence of systematic differences. Additionally, we analysed the total brain volumes, which showed to be similarly consistent across groups. Moreover, should there be systematic differences, the subcortical volumes extracted should show differences across the groups in a way that align with the differences in the scanners/protocols. Our results, however, revealed patterns that did not match up with scanner differences. For example, bilinguals and trilinguals did not show systematic similarities, even with the same scanner/protocol. Furthermore, they exhibited both similar and distinct volumes compared to the other two groups scanned using different protocols/scanners. This method has also been used in other studies involving multiple scanners (Elkattan et al., 2017; Pliatsikas et al., 2020b). This being said, using data from different protocols is not ideal, and future studies facing the same issue of not being able to obtain data from the same environment could consider scanning a small number of reference participants using the different acquisition protocols to verify the absence of any systematic differences.

Other potential limitations of this study include the lack of SES reports from participants and cultural differences between the monolinguals from the UK, bilinguals and trilinguals from Malaysia and quadrilinguals from the Czech Republic. It is plausible that some unmeasured lifestyle variables differed between the groups and had an influence on experience-dependent neuroplasticity that contributed to the differences found in structural adaptations. However, while it is not possible to address all possible confounds in a single study (Bak, 2016), the English monolinguals were selected because of the difficulty of finding comparable monolinguals in Malaysia. Typically, in Malaysia, monolinguals tend to be from a much older age-group and have a lower level

of education than the multilingual population. Furthermore, the assumed monolinguals in Malaysia are likely to have been exposed to many other languages and dialects such as English and Chinese. In light of these differences, monolinguals in the UK were chosen as the baseline group instead of Malaysian monolinguals as the latter would have had jarring differences in education level and age when compared to the multilingual groups, potentially confounding any structural variation found.

In conclusion, subcortical adaptations are dynamic in that they are not fixed across all structures and do not all proceed at the same rate. The use of two languages is associated with increased subcortical volumes, and further language experience in the form of knowing more languages is associated with smaller volumes which are similar to that of monolinguals. The pattern of changes seems to consist of expansions followed by contractions, which may be interpreted as renormalisation and optimisation of neural resources as experience mounts. The subcortical structures that adapt the fastest appear to be structures with central roles in domain-general cognitive functions (i.e., cognitive control) that are similarly vital in handling multiple languages. All in all, these findings highlight the remarkable ability of the brain to continually reorganise to achieve and maintain efficiency; allowing humans to do more with less.

Supplementary Material. To view supplementary material for this article, please visit <https://doi.org/10.1017/S136672892300086X>

The volumes of the analysed subcortical structures can be found as supplementary material accompanying this paper.

Data Availability. The data analysed for this study are included in this published article as a supplementary information file.

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Competing interests. The authors declare none.

References

- Abela, A. R., Duan, Y., & Chudasama, Y. (2015). Hippocampal interplay with the nucleus accumbens is critical for decisions about time. *European Journal of Neuroscience*, *42*(5), 2224–2233.
- Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., Lazeyras, F., Cappa, S. F., & Khateb, A. (2008). Language control and lexical competition in bilinguals: an event-related fMRI study. *Cerebral Cortex*, *18*(7), 1496–1505. <https://doi.org/10.1093/cercor/bhm182>
- Abutalebi, J., Della Rosa, P. A., Gonzaga, A. K. C., Keim, R., Costa, A., & Perani, D. (2013). The role of the left putamen in multilingual language production. *Brain and Language*, *125*(3), 307–315.
- Abutalebi, J., & Green, D. W. (2016). Neuroimaging of language control in bilinguals: neural adaptation and reserve. *Bilingualism: Language and Cognition*, *19*(4), 689–698. <https://doi.org/10.1017/S1366728916000225>
- Adamson, M. M., Taylor, J. L., Heraldez, D., Khorasani, A., Noda, A., Hernandez, B., & Yesavage, J. A. (2014). Higher landing accuracy in expert pilots is associated with lower activity in the caudate nucleus. *PLoS one*, *9*(11), e112607. <https://doi.org/10.1371/journal.pone.0112607>
- Alain, C., Reinke, K., McDonald, K. L., Chau, W., Tam, F., Pacurar, A., & Graham, S. (2005). Left thalamo-cortical network implicated in successful speech separation and identification. *NeuroImage*, *26*(2), 592–599. <https://doi.org/10.1016/j.neuroimage.2005.02.006>
- Anderson, J. A. E., Mak, L., Keyvani Chahi, A., & Bialystok, E. (2018). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behavior Research Methods*, *50*(1), 250–263. <https://doi.org/10.3758/s13428-017-0867-9>
- Aparicio, X., & Lavour, J. M. (2014). Recognising words in three languages: effects of language dominance and language switching. *International Journal of Multilingualism*, *11*(2), 164–181. <https://doi.org/10.1080/14790718.2013.783583>
- Bak, T. H. (2016). The impact of bilingualism on cognitive ageing and dementia: Finding a path through a forest of confounding variables. *Linguistic Approaches to Bilingualism*, *6*(1-2), 205–226.
- Bast, A., Guest, J. M., Fruengel, R., Narayanan, R. T., de Kock, C. P., & Oberlander, M. (2021). Thalamus drives active dendritic computations in cortex. *bioRxiv*, 2021-10.
- Bialystok, E. (2007). Cognitive effects of bilingualism: How linguistic experience leads to cognitive change. *International Journal of Bilingual Education and Bilingualism*, *10*(3), 210–223.
- Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: consequences for mind and brain. *Trends in Cognitive Sciences*, *16*(4), 240–250. <https://doi.org/10.1016/j.tics.2012.03.001>
- Bradley, K. A., King, K. E., & Hernandez, A. E. (2013). Language experience differentiates prefrontal and subcortical activation of the cognitive control network in novel word learning. *NeuroImage*, *67*, 101–110. doi: 10.1016/j.neuroimage.2012.11.018
- Brilliant, T. D., Nouchi, R., & Kawashima, R. (2019). Does video gaming have impacts on the brain: Evidence from a systematic review. *Brain Sciences*, *9*(10), 251. <https://doi.org/10.3390/brainsci9100251>
- Brovelli, A., Nazarian, B., Meunier, M., & Boussaoud, D. (2011). Differential roles of caudate nucleus and putamen during instrumental learning. *NeuroImage*, *57*(4), 1580–1590. <https://doi.org/10.1016/j.neuroimage.2011.05.059>
- Burgaleta, M., Sanjuán, A., Ventura-Campos, N., Sebastian-Galles, N., & Ávila, C. (2016). Bilingualism at the core of the brain. Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *NeuroImage*, *125*, 437–445. <https://doi.org/10.1016/j.neuroimage.2015.09.07>
- Costa, A., Foucart, A., Arnon, I., Aparici, M., & Apesteguia, J. (2014). “Piensa” twice: On the foreign language effect in decision making. *Cognition*, *130*(2), 236–254. <https://doi.org/10.1016/j.cognition.2013.11.010>
- Costumero, V., Marin-Marín, L., Calabria, M., Bellocchio, V., Escudero, J., Baquero, M., Hernandez, M., Ruiz de Miras, J., Costa, A., Parcet, M. A., & Ávila, C. (2020). A cross-sectional and longitudinal study on the protective effect of bilingualism against dementia using brain atrophy and cognitive measures. *Alzheimer's Research & Therapy*, *12*(1), 1–10. <https://doi.org/10.1186/s13195-020-0581-1>
- Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., Aso, T., Urayama, S., Fukuyama, H., Stockton, K., Usui, K., Green, D. W., & Price, C. J. (2006). Language control in the bilingual brain. *Science*, *312*(5779), 1537–1540. <https://doi.org/10.1126/science.1127761>
- De Baene, W., Duyck, W., Brass, M., & Carreiras, M. (2015). Brain circuit for cognitive control is shared by task and language switching. *Journal of Cognitive Neuroscience*, *27*(9), 1752–1765. https://doi.org/10.1162/jocn_a_00817
- Della Rosa, P. A., Videsott, G., Borsa, V. M., Canini, M., Weekes, B. S., Franceschini, R., & Abutalebi, J. (2013). A neural interactive location for multilingual talent. *Cortex*, *49*(2), 605–608. <https://doi.org/10.1016/j.cortex.2012.12.001>
- DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019a). Redefining bilingualism as a spectrum of experiences that differentially affects brain

- structure and function. *Proceedings of the National Academy of Sciences*, 116 (15), 7565–7574. <https://doi.org/10.1073/pnas.1811513116>
- DeLuca, V., Rothman, J., & Pliatsikas, C. (2019b). Linguistic immersion and structural effects on the bilingual brain: a longitudinal study. *Bilingualism: Language and Cognition*, 22(5), 1160–1175. Doi: <https://doi.org/10.1017/S1366728918000883>
- Elkattan, A., Mahdy, A., Eltomey, M., & Ismail, R. (2017). A Study of volumetric variations of basal nuclei in the normal human brain by magnetic resonance imaging. *Clinical Anatomy*, 30(2), 175–182.
- Elmer, S., Hänggi, J., & Jäncke, L. (2014). Processing demands upon cognitive, linguistic, and articulatory functions promote grey matter plasticity in the adult multilingual brain: Insights from simultaneous interpreters. *Cortex*, 54, 179–189. <https://doi.org/10.1016/j.cortex.2014.02.014>
- Fabbro, F., Vorano, L., Fabbro, S., & Tavano, A. (2002). Language disorders following lesions to the thalamus and basal ganglia. *European Journal of Physical and Rehabilitation Medicine*, 38(4), 203.
- Fazl, A., & Fleisher, J. (2018). Anatomy, physiology, and clinical syndromes of the basal ganglia: a brief review. *Seminars in Pediatric Neurology*, 25, 2–9.
- Feinberg, I. (1982). Schizophrenia: caused by a fault in programmed synaptic elimination during adolescence?. *Journal of Psychiatric Research*, 17(4), 319–334.
- Floresco, S. B. (2015). The nucleus accumbens: an interface between cognition, emotion, and action. *Annual Review of Psychology*, 66, 25–52. <https://doi.org/10.1146/annurev-psych-010213-115159>
- García-Pentón, L., Fernández, A. P., Iturria-Medina, Y., Gillon-Dowens, M., & Carreiras, M. (2014). Anatomical connectivity changes in the bilingual brain. *NeuroImage*, 84, 495–504. <https://doi.org/10.1016/j.neuroimage.2013.08.064>
- Gerber, P., Schlaffke, L., Heba, S., Greenlee, M. W., Schultz, T., & Schmidt-Wilcke, T. (2014). Juggling revisited—A voxel-based morphometry study with expert jugglers. *NeuroImage*, 95, 320–325.
- Gooijers, J., Chalavi, S., Beeckmans, K., Michiels, K., Lafosse, C., Sunaert, S., & Swinnen, S. P. (2016). Subcortical volume loss in the thalamus, putamen, and pallidum, induced by traumatic brain injury, is associated with motor performance deficits. *Neurorehabilitation and Neural Repair*, 30(7), 603–614. <https://doi.org/10.1177/1545968315613448>
- Grazioplene, R. G., G. Ryan, S., Gray, J. R., Rustichini, A., Jung, R. E., & DeYoung, C. G. (2015). Subcortical intelligence: Caudate volume predicts IQ in healthy adults. *Human Brain Mapping*, 36(4), 1407–1416.
- Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, 1(2), 67–81. <https://doi.org/10.1017/S1366728998000133>
- Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, 25(5), 515–530. <https://doi.org/10.1080/20445911.2013.796377>
- Green, D. W., & Kroll, J. F. (2019). The neurolinguistics of bilingualism. In G. I. de Zubicaray & N. O. Schiller (Eds.), *The Oxford Handbook of Neurolinguistics* (pp. 261–294). New York: Oxford University Press.
- Grillner, S., & Robertson, B. (2016). The basal ganglia over 500 million years. *Current Biology*, 26(20), R1088–R1100.
- Grogan, A., Jones, Ö. P., Ali, N., Crinion, J., Orabona, S., Mechias, M. L., Ramsden, S., Green, D. W., & Price, C. J. (2012). Structural correlates for lexical efficiency and number of languages in non-native speakers of English. *Neuropsychologia*, 50(7), 1347–1352.
- Grundy, J. G., Anderson, J. A., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences*, 1396(1), 183–201. <https://doi.org/10.1111/nyas.13333>
- Hänggi, J., Koeneke, S., Bezzola, L., & Jäncke, L. (2010). Structural neuroplasticity in the sensorimotor network of professional female ballet dancers. *Human Brain Mapping*, 31(8), 1196–1206.
- Hayakawa, S., Costa, A., Foucart, A., & Keysar, B. (2016). Using a foreign language changes our choices. *Trends in Cognitive Sciences*, 20(11), 791–793. <https://doi.org/10.1016/j.tics.2016.08.004>
- Hayakawa, S., & Marian, V. (2019). Consequences of multilingualism for neural architecture. *Behavioral and Brain Functions*, 15(1), 1–24. <https://doi.org/10.1186/s12993-019-0157-z>
- Heim, S., Stumme, J., Bittner, N., Jockwitz, C., Amunts, K., & Caspers, S. (2019). Bilingualism and “brain reserve”: a matter of age. *Neurobiology of Aging*, 81, 157–165. <https://doi.org/10.1016/j.neurobiolaging.2019.05.021>
- Hervais-Adelman, A., Egorova, N., & Golestani, N. (2018). Beyond bilingualism: multilingual experience correlates with caudate volume. *Brain Structure and Function*, 223, 3495–3502. <https://doi.org/10.1007/s00429-018-1695-0>
- Hwang, K., Shine, J. M., Bruss, J., Tranel, D., & Boes, A. (2021). Neuropsychological evidence of multi-domain network hubs in the human thalamus. *eLife*, 10, e69480.
- Jacquemot, C., & Bachoud-Lévi, A. C. (2021). Striatum and language processing: Where do we stand?. *Cognition*, 213, 104785. <https://doi.org/10.1016/j.cognition.2021.104785>
- Janacek, K., Shattuck, K. F., Tagarelli, K. M., Lum, J. A., Turkeltaub, P. E., & Ullman, M. T. (2020). Sequence learning in the human brain: A functional neuroanatomical meta-analysis of serial reaction time studies. *NeuroImage*, 207, 116387. <https://doi.org/10.1016/j.neuroimage.2019.116387>
- Javed, N., & Cascella, M. (2020). *Neuroanatomy, Globus Pallidus*. Treasure Island (FL): StatPearls Publishing.
- Klein, D., Mok, K., Chen, J. K., & Watkins, K. E. (2014). Age of language learning shapes brain structure: a cortical thickness study of bilingual and monolingual individuals. *Brain and Language*, 131, 20–24. <https://doi.org/10.1016/j.bandl.2013.05.014>
- Klostermann, F., Krugel, L. K., & Ehlen, F. (2013). Functional roles of the thalamus for language capacities. *Frontiers in Systems Neuroscience*, 7, 32.
- Koikkalainen, J., Hirvonen, J., Nyman, M., Lötjönen, J., Hietala, J., & Ruotsalainen, U. (2007). Shape variability of the human striatum—effects of age and gender. *NeuroImage*, 34(1), 85–93.
- Korenar, M., Treffers-Daller, J., & Pliatsikas, C. (2023). Dynamic effects of bilingualism on brain structure map onto general principles of experience-based neuroplasticity. *Scientific Reports*, 13(1), 3428.
- Kroll, J. F., Bobb, S. C., & Hoshino, N. (2014). Two languages in mind: Bilingualism as a tool to investigate language, cognition, and the brain. *Current Directions in Psychological Science*, 23(3), 159–163. <https://doi.org/10.1177/0963721414528511>
- Legault, J., Grant, A., Fang, S. Y., & Li, P. (2019). A longitudinal investigation of structural brain changes during second language learning. *Brain and Language*, 197, 104661.
- Lemhöfer, K., Dijkstra, T., & Michel, M. (2004). Three languages, one ECHO: Cognate effects in trilingual word recognition. *Language and Cognitive Processes*, 19(5), 585–611. <https://doi.org/10.1080/01690960444000007>
- Li, P., Legault, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: Anatomical changes in the human brain. *Cortex*, 58, 301–324.
- Liu, H., Hu, Z., Guo, T., & Peng, D. (2010). Speaking words in two languages with one brain: Neural overlap and dissociation. *Brain Research*, 1316, 75–82.
- Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and Cognitive Processes*, 27(10), 1479–1488.
- Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research*, 50(4), 940–967.
- Marian, V., Blumenfeld, H. K., Mizrahi, E., Kania, U., & Cordes, A. K. (2013). Multilingual Stroop performance: Effects of trilingualism and proficiency on inhibitory control. *International Journal of Multilingualism*, 10(1), 82–104.
- Marian, V., & Spivey, M. (2003). Competing activation in bilingual language processing: Within- and between-language competition. *Bilingualism: Language and Cognition*, 6(2), 97–115. <https://doi.org/10.1017/S1366728903001068>
- Marin-Marín, L., Costumero, V., Ávila, C., & Pliatsikas, C. (2022). Dynamic effects of immersive bilingualism on cortical and subcortical grey matter volumes. *Frontiers in Psychology*, 13, 886222.
- Mårtensson, J., Eriksson, J., Bodammer, N. C., Lindgren, M., Johansson, M., Nyberg, L., & Lövdén, M. (2012). Growth of language-related brain areas after foreign language learning. *NeuroImage*, 63(1), 240–244.
- Masouleh, S. K., Eickhoff, S. B., Hoffstaedter, F., Genon, S., & Alzheimer’s Disease Neuroimaging Initiative. (2019). Empirical examination of the replicability of associations between brain structure and psychological variables. *eLife*, 8.
- Meyer, H. C., & Bucci, D. J. (2016). Imbalanced activity in the orbitofrontal cortex and nucleus accumbens impairs behavioral inhibition. *Current Biology*, 26(20), 2834–2839.

- Midrigan-Ciochina, L., Vodacek, K. P., Balabhadra, S., & Corina, D. P. (2023). A comparison of structural brain differences in monolingual and highly proficient multilingual speakers. *Bilingualism: Language and Cognition*, 1-11.
- Murdoch, B. E. (2009). *Speech and language disorders associated with subcortical pathology*. West Sussex: John Wiley & Sons.
- Nadeau, S. E., & Crosson, B. (1997). Subcortical aphasia. *Brain and Language*, 58(3), 355-402.
- Navlakha, S., Barth, A. L., & Bar-Joseph, Z. (2015). Decreasing-rate pruning optimizes the construction of efficient and robust distributed networks. *PLoS Computational Biology*, 11(7), e1004347.
- Oertel, W., & Schulz, J. B. (2016). Current and experimental treatments of Parkinson disease: A guide for neuroscientists. *Journal of Neurochemistry*, 139, 325-337.
- Olszewska, A. M., Gaca, M., Herman, A. M., Jednoróg, K., & Marchewka, A. (2021). How musical training shapes the adult brain: Predispositions and neuroplasticity. *Frontiers in Neuroscience*, 15, 630829. <https://doi.org/10.3389/fnins.2021.630829>
- Patenaude, B., Smith, S. M., Kennedy, D. N., & Jenkinson, M. (2011). A Bayesian model of shape and appearance for subcortical brain segmentation. *NeuroImage*, 56(3), 907-922.
- Pliatsikas, C. (2019). Multilingualism and brain plasticity. In J. Schwieter & M. Paradis (Eds.), *The handbook of the neuroscience of multilingualism* (pp. 230-251). New Jersey: Wiley-Blackwell.
- Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. *Bilingualism: Language and Cognition*, 23(2), 459-471.
- Pliatsikas, C., DeLuca, V., Moschopoulou, E., & Saddy, J. D. (2017). Immersive bilingualism reshapes the core of the brain. *Brain Structure and Function*, 222(4), 1785-1795.
- Pliatsikas, C., DeLuca, V., & Voits, T. (2020a). The many shades of bilingualism: Language experiences modulate adaptations in brain structure. *Language Learning*, 70(S2), 133-149. <https://doi.org/10.1111/lang.12386>
- Pliatsikas, C., Meteyard, L., Verissimo, J., DeLuca, V., Shattuck, K., & Ullman, M. T. (2020b). The effect of bilingualism on brain development from early childhood to young adulthood. *Brain Structure and Function*, 225(7), 2131-2152.
- Poarch, G. J., & Van Hell, J. G. (2014). Cross-language activation in same-script and different-script trilinguals. *International Journal of Bilingualism*, 18(6), 693-716. <https://doi.org/10.1177/1367006912472262>
- Prasad, A. S. V. (2020). Physiological basis of memory dysfunction in Alzheimer's disease—an overview. *International Journal of Biochemistry Research & Review*, 29(2), 9-24.
- Raji, C. A., Meysami, S., Merrill, D. A., Porter, V. R., & Mendez, M. F. (2020). Brain structure in bilingual compared to monolingual individuals with Alzheimer's disease: Proof of concept. *Journal of Alzheimer's Disease*, 76(1), 275-280.
- Resende, E. D. P. F., Tovar-Moll, F. F., Ferreira, F. M., Bramati, I., de Souza, L. C., Carmona, K. C., Guimarães, H. C., Carvalho, V. A., Barbosa, M. T., & Caramelli, P. (2018). White matter microstructure in illiterate and low-literate elderly Brazilians: preliminary findings. *Cognitive and Behavioral Neurology*, 31(4), 193-200.
- Rothman, J., Alonso, J. G., & Puig-Mayenco, E. (2019). *Third language acquisition and linguistic transfer* (Vol. 163). Cambridge: Cambridge University Press. doi:10.1017/9781316014660
- Saleem, M., & Samudrala, P. (2017). Meditation experience associated with structural neuroplasticity. *Annals of International Medical and Dental Research*, 3(4), 1.
- Schroeder, S. R., & Marian, V. (2017). Cognitive consequences of trilingualism. *International Journal of Bilingualism*, 21, 754-773. <https://doi.org/10.1177/1367006916637288>
- Segall, J. M., Allen, E. A., Jung, R. E., Erhardt, E. B., Arja, S. K., Kiehl, K., & Calhoun, V. D. (2012). Correspondence between structure and function in the human brain at rest. *Frontiers in Neuroinformatics*, 6, 10.
- Spear, L. P. (2013). Adolescent neurodevelopment. *Journal of Adolescent Health*, 52(2), S7-S13. <https://doi.org/10.1016/j.jadohealth.2012.05.006>
- Syka, M., Keller, J., Klempf, J., Rulseh, A. M., Roth, J., Jech, R., Vorisek, I., & Vymazal, J. (2015). Correlation between relaxometry and diffusion tensor imaging in the globus pallidus of Huntington's disease patients. *PLoS one*, 10(3), e0118907.
- Tomasi, D., & Volkow, N. D. (2012). Resting functional connectivity of language networks: characterization and reproducibility. *Molecular Psychiatry*, 17(8), 841-854.
- Tremblay, M. C., & Sabourin, L. (2012). Comparing behavioral discrimination and learning abilities in monolinguals, bilinguals and multilinguals. *The Journal of the Acoustical Society of America*, 132(5), 3465-3474.
- Verstynen, T. D., Lynch, B., Miller, D. L., Voss, M. W., Prakash, R. S., Chaddock, L., Basak, C., Szabo, A., Olson, E. A., Wojcicki, T. R., Fanning, J., Gothe, N. P., McAuley, E., Kramer, A. F., & Erickson, K. I. (2012). Caudate nucleus volume mediates the link between cardiorespiratory fitness and cognitive flexibility in older adults. *Journal of Aging Research*, 2012 (Special Issue), 939285. <https://doi.org/10.1155/2012/939285>
- Viñas-Guasch, N., & Wu, Y. J. (2017). The role of the putamen in language: a meta-analytic connectivity modeling study. *Brain Structure and Function*, 222, 3991-4004.
- Wahl, M., Marzinzik, F., Friederici, A. D., Hahne, A., Kupsch, A., Schneider, G. H., Saddy, D., Curio, G., & Klostermann, F. (2008). The human thalamus processes syntactic and semantic language violations. *Neuron*, 59(5), 695-707.
- Wang, Y., Lu, Y., Deng, Y., Gu, N., Parviainen, T., & Zhou, C. (2019). Predicting domain-specific actions in expert table tennis players activates the semantic brain network. *NeuroImage*, 200, 482-489.
- Ward, L. M. (2013). The thalamus: gateway to the mind. *Wiley Interdisciplinary Reviews: Cognitive Science*, 4(6), 609-622.
- Wenger, E., Brozzoli, C., Lindenberger, U., & Lövdén, M. (2017). Expansion and renormalization of human brain structure during skill acquisition. *Trends in Cognitive Sciences*, 21(12), 930-939.
- Whelan, B. M., Murdoch, B. E., Theodoros, D. G., Darnell, R., Silburn, P., & Hall, B. (2004). Redefining functional models of basal ganglia organization: role for the posteroventral pallidum in linguistic processing?. *Movement Disorders: Official Journal of the Movement Disorder Society*, 19(11), 1267-1278.
- Zou, L., Ding, G., Abutalebi, J., Shu, H., & Peng, D. (2012). Structural plasticity of the left caudate in bimodal bilinguals. *Cortex*, 48(9), 1197-1206.

Appendix

Table 2. Summary of language variety used by participants.

Group	Number of Participants (females)	Language(s)	Number of users	AoA (SD)
Monolinguals	14 (13)	English	14	0
Bilinguals	14 (12)	English	14	6 (3.1)
		Malay	14	2.5 (1.6)
Trilinguals	14 (10)	English	14	4.43 (1.69)
		Malay	14	4.3 (1.8)
		Chinese	11	1.91 (1.14)
		Tamil	1	5
		Korean	1	15
		Japanese	1	13
Quadilinguals	14 (9)	English	14	9 (2.9)
		Czech	14	0.2 (0.8)
		German	9	12 (2.8)
		French	6	13.2 (4.5)
		Spanish	4	18 (3.2)
		Russian	3	12.3 (11)
		Norwegian	2	25 (5.7)
		Hungarian	1	0
		Irish	1	17
		Italian	1	12
Slovak	1	6		

Table 4. Means and standard deviations of raw (mm³) and normalised (%) subcortical volumes.

Subcortical region	Hemi-sphere	Monolinguals (N = 14)		Bilinguals (N = 14)		Trilinguals (N = 14)		Quadrilinguals (N = 14)	
		Raw	Normalised	Raw	Normalised	Raw	Normalised	Raw	Normalised
Caudate nucleus	L	3634.75 (518.56)	0.263 (0.039)	3749.48 (341.09)	0.287 (0.024)	3703.75 (305.84)	0.268 (0.022)	3983.72 (419.60)	0.285 (0.156)
	R	3776.38 (388.56)	0.272 (0.025)	3590.65 (353.84)	0.274 (0.019)	3676.46 (430.37)	0.266 (0.026)	4099.81 (372.10)	0.294 (0.018)
Nucleus accumbens	L	503.94 (131.11)	0.036 (0.009)	581.28 (114.44)	0.044 (0.007)	550.44 (105.94)	0.040 (0.007)	570.19 (134.09)	0.041 (0.008)
	R	424.17 (112.27)	0.030 (0.008)	509.81 (55.49)	0.039 (0.005)	446.98 (60.78)	0.032 (0.003)	516.56 (104.96)	0.037 (0.006)
Putamen	L	4660.78 (509.53)	0.337 (0.038)	5436.65 (466.14)	0.416 (0.032)	5732.0 (493.12)	0.415 (0.035)	5016.33 (562.19)	0.359 (0.025)
	R	4596.62 (359.14)	0.332 (0.031)	5292.02 (499.87)	0.404 (0.026)	5437.13 (435.71)	0.394 (0.033)	4975.80 (496.12)	0.356 (0.021)
Globus pallidus	L	1593.73 (89.15)	0.115 (0.007)	1797.82 (118.61)	0.138 (0.008)	1877.20 (179.18)	0.136 (0.010)	1805.77 (214.99)	0.129 (0.010)
	R	1587.58 (91.63)	0.115 (0.007)	1778.14 (172.89)	0.136 (0.009)	1850.26 (186.48)	0.134 (0.010)	1771.84 (226.53)	0.127 (0.011)
Thalamus	L	7601.71 (513.75)	0.548 (0.026)	8506.97 (525.39)	0.651 (0.035)	8714.91 (743.73)	0.631 (0.055)	8444.83 (883.87)	0.604 (0.031)
	R	7440.99 (507.30)	0.537 (0.027)	8115.87 (437.90)	0.621 (0.032)	8454.78 (840.02)	0.612 (0.051)	8336.05 (946.22)	0.595 (0.026)
Brainstem		20076.87 (2697.32)		20798.08 (2362.40)		21764.18 (2612.13)		23650.51 (2842.99)	
Total brain volume		1388139.07 (101262.36)		1309427.43 (100885.17)		1386849.07 (136648.21)		1400098.00 (145233.08)	

Note. L refers to Left and R to Right. Normalised volumes are subcortical volumes as a proportion of total brain volume (raw volume/total brain volume*100).