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Brain structure adapts dynamically to highly demanding bilingual experiences: Insights from interpreters and translators

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A B S T R A C T

It remains an open question how the brain adapts structurally to handle strenuous cognitive challenges. Interpreters and translators rely on high cognitive control to regulate two languages in their jobs, which makes them ideal models in investigating experience-based neuroplasticity induced by exceptional cognitive demands. Using structural MRI, we compare volumes of the caudate nucleus and putamen, structures involved in bilingual language control, in three groups of highly experienced bilinguals: translators, interpreters and highly experienced bilinguals. Between-group comparisons revealed larger volumes for both structures in interpreters and translators compared to highly experienced bilinguals. We used Bayesian Generalized Additive Mixed Models to model effects of quantified general bilingual experiences on the structures of interest. Critically, dynamic, group-specific volumetric trajectories of the ROIs related to general bilingual experiences were revealed. Specifically, whereas caudate volumes increased as a function of bilingual experiences across all groups, they started to return to baseline volumes at the high points of experiences in the two professional groups only. As for the putamen, the expansion-renormalisation pattern was replicated in interpreters only, whereas in translators and highly experienced controls, putamen volumes simply increased as a function of bilingual experiences. This pattern of results suggests that bilingualism-related brain adaptations manifest differently in different brain regions and are modulated by quantitative and qualitative differences in bilingual experiences. These findings shed new light on the ways in which extremely demanding bilingual experiences affect neuroplasticity in bilinguals.

1. Introduction

Evidence that demanding experiences induce neuroplasticity has recently attracted attention from researchers across the world. Neuroplasticity has been suggested to have important implications for the amelioration of cognitive decline (Sikkes et al., 2021) and effective acquisition of new skills (Olszewska et al., 2021). An example of such an experience is bilingualism (Gallo et al., 2020). Considerable research has focused on disentangling the mechanisms behind brain changes brought about by bilingualism. However, existing studies have so far yielded inconsistent results in terms of the location and direction of the structural brain changes, partly because our understanding of such adaptations in bilinguals with extreme experiences is very limited (Hervais-Adelman et al., 2017; Muñoz et al., 2019). Furthermore, recent findings suggest that bilingualism, similarly to other demanding experiences, induces structural brain adaptions that are dynamic and depend on the intensity and amount of the relevant experiences (Korenar et al., 2023a; Korenar et al., 2022; Marin-Marin et al., 2022; Pliatsikas, 2020).

To fully understand the transformative power of bilingualism on the brain, a better understanding is needed of the effects of the wide spectrum of bilingual experiences, including highly challenging ones, with a view to unravel which of these are most likely to change our brain dynamically. For this reason, we investigate here the structural brain alterations in relatively under-researched groups of bilinguals with exceptional, long-standing, and sustained engagement with both languages they speak, namely interpreters and translators. Furthermore, this study aims to estimate whether the brain's structural response to the spectrum of general bilingual practices is different among translators,

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interpreters, and bilinguals without any professional training. Such an approach could not only inform theoretical frameworks describing effects of bilingualism on brain structure, but also broaden our understanding of neuroplasticity in general.

1.1. Structural neuroplasticity in bilinguals

Bilingualism induces brain adaptations which have been suggested to result from the constant need of bilinguals to choose between two competing linguistic alternatives and switch between them (Li et al., 2017). Such a relentless mental conflict is suggested to pose excessive demands for cognitive processes necessary for language control and cognitive control in general (Kroll et al., 2012), which do not apply to users of a single language. As a result, the brain adapts structurally in brain regions responsible for cognitive control processes which help dealing effectively with two concurrently activated languages.

Bilingual practices have been consistently linked to brain adaptations of areas in the basal ganglia, such as the caudate nucleus, nucleus accumbens, putamen, and globus pallidus (Burgaleta et al., 2016; DeLuca et al., 2019a; Hervais-Adelman et al., 2018; Korenar et al., 2022, 2023a; Pliatsikas et al., 2017). The basal ganglia likely serve as gate-keepers, orchestrating our responses to external and internal stimuli, including regulation of cognitive control processes in bilinguals (Green and Kroll, 2019). However, the needs for bilinguals to use their languages, and their habitual language practices impact the levels of cognitive demands. Consequently, reliance on these structures is expected to vary across bilingual groups and across individuals with different bilingual experiences.

The idea that bilingualism may have variable effects on the brain depending on individual differences in bilingual language use is central to *the Dynamic Restructuring Model* (DRM, Pliatsikas, 2020). This model synthesised available literature on neuroplasticity in the context of bilingualism and put forth the following prediction: Bilingualism-induced brain changes follow a so-called *expansion-renormalisation trajectory*, like many other demanding experiences do (Wenger et al., 2017). That is, bilingual experiences likely trigger an initial increase of grey matter, followed by volumetric decreases in highly experienced individuals as a result of optimisation of the existing neural resources (Pliatsikas, 2020). Furthermore, these adaptations are assumed to follow a timeline that reflects which cognitive processes are required by bilinguals at various stages of their bilingual experiences. Now we will turn to the description of the three stages as hypothesised by the DRM.

The DRM proposes three stages which are marked by differences in relative reliance on various skills necessary to control for concurrent activation of two languages. At the first stage, bilinguals are gradually exposed to a second language. This process involves learning how to acquire both vocabulary and control for language alternatives. This stage is marked by increases of the caudate as a structure subserving the required cognitive control processes (Abutalebi and Green, 2016). In the second stage, the cognitive demands shift from vocabulary acquisition to grammar and phonological acquisition and finetuning of efficiency in cognitive control (Caffarra et al., 2015; Pliatsikas and Marinis, 2013). This is where adaptations in cerebellar regions and other subcortical regions, including putamen, begin to emerge, as these structures are involved in these processes. In the third stage, the grey matter changes in the caudate which occurred during the previous stages slowly renormalise due to increasing efficiencies in the neural network underlying bilingual language control. For these effects to occur, a long-standing and continuous experience with bilingualism is necessary. Therefore, the third stage assumes to pertain to the brain adaptations occurring in exceptionally experienced bilinguals. However, the last stage is the least well-documented part of the model, due to the limited number of studies investigating structural brain changes in highly experienced bilinguals. The limited available evidence documented for this stage comes largely from studies on simultaneous interpreters who are expected to be typical representatives of this stage, as will be discussed in the next section.

A recent study on bilinguals with a rich array of experiences aimed to directly test the predictions of the DRM (Korenar et al., 2023a; for similar approach see also Marin-Marin et al., 2022). Bilingual experiences measured as continuous variables were used as predictors of volumes of the basal ganglia and the thalamus using Generalized Additive Mixed Models (GAMMs), which can capture potential non-linear effects. The findings suggest that the caudate nucleus is the first structure in the basal ganglia to renormalise in volume in highly experienced bilinguals, in line with its stated importance in particular in the early stages of bilingualism. By contrast, bilingual experiences predicted larger volumes of the putamen and thalamus without any signs of renormalisation. This may be due to the functional specialisation of the putamen, which would likely require long-standing and intensive experiences in articulatory control to renormalise. In all, the study elucidated the dynamic effects of bilingual experiences on grey matter volumes. However, the results do not inform us on the specific effects of professional bilingual experiences like those of interpreters and translators.

1.2. Interpreters and translators

Interpreters and translators are special cases of bilinguals who use both of their languages on a daily basis, switch between them regularly, and who constantly need to perceive messages in one language and reformulate them in another one (Muñoz et al., 2019). The cognitive processes utilised to execute these activities do not necessarily differ from those used by bilinguals who do not engage in translating and interpreting practices (henceforth *highly experienced bilinguals*) in their everyday lives (Korenar et al., 2023b). However, professional bilingual practices likely engage these processes more intensively (García et al., 2020). It follows then that the effects on brain structure may also differ in terms of their location, magnitude and/or trajectory when compared to those reported in highly experienced bilinguals.

The caudate nucleus and the putamen are two regions identified as central for both simultaneous interpreting (Diamond and Shreve, 2019; Elmer, 2016; Hervais-Adelman et al., 2015) and translating (e.g. Lehtonen et al., 2005; Price et al., 1999). For example, in a recent fMRI study, Hervais-Adelman et al. (2015) examined the activation of both regions in multilingual participants (including novice interpreters) in two tasks. First, in an interpreting task, participants were listening to a stream of speech in their highly proficient language while producing its translation in their native language. Second, during a shadowing task, participants simultaneously listened to and repeated sentences in the same language. The authors reported increased activation in the caudate nucleus in the bilingual interpreting condition compared to the shadowing condition, but no significant differences in the activation of the putamen. Furthermore, the authors investigated differences in brain activity triggered by the level of simultaneity in both tasks, i.e. the extent of time overlap between the speech input and speech production. Their results revealed that the right putamen's activation was significantly greater in the interpreting condition than in the shadowing condition. Moreover, the length of the overlap between the input and output speech in the interpreting condition appeared to make the difference in activation difference even stronger. Simultaneity did not emerge as significant modulatory factor for the activity of the caudate nucleus. These findings highlight that the two structures do not have the same roles during simultaneous interpreting.

The distinction between functionality of the caudate and the putamen during simultaneous interpreting has been recently described in the *Neurocognitive model of simultaneous interpreting* (NMSI; Hervais-Adelman and Babcock, 2020). This model posits two functionally distinct control pathways centered upon these two structures. Specifically, the caudate nucleus is hypothesised to subserve monitoring and the selection of the appropriate linguistic system, whereas the putamen secures the suppression of the inappropriate language on a moment-to-moment basis and regulates simultaneously executed processes (Hervais-Adelman and Babcock, 2020). It follows then that the different roles of the two structures are likely to undergo structural changes that not only differ to those reported in highly experienced bilinguals, even experienced ones, but also to each other, in terms of their timeline, trajectory and magnitude.

Indeed, with respect to structural brain changes in the context of simultaneous interpreting, two studies have investigated effects on grey matter, with one of them informing the predictions of the DRM (Elmer et al., 2014). Elmer and colleagues compared volumes of grey matter in simultaneous interpreters and multilinguals in a-priori defined regions of interest (ROIs) derived from the functional-anatomical framework proposed by Abutalebi and Green (2007), including the caudate nucleus (but not the putamen). The analysis revealed that interpreters had smaller grey matter volumes than multilinguals in several regions subserving language control, i.e., the left cingulate gyrus, bilateral inferior frontal gyrus, insula, and superior medial gyrus, but not the caudate nucleus. The authors ascribed the lack of effects in the caudate nucleus to the small sample size (12 interpreters and 12 multilingual controls) and low statistical power (Elmer et al., 2014). However, viewed from the DRM perspective, it is also possible that the caudate nucleus was in the process of renormalising for the SI group-however, the small sample size does not allow for a safe interpretation. The authors also performed a correlational analysis within the SI group and revealed that the volumes of bilateral caudate nuclei were negatively correlated with the number of hours of interpreting experience. The authors explained this finding as an indication of renormalisation of the caudate nucleus, which would reflect specialisation of this region in language control toward higher efficiency (as it is also predicted by the DRM).

The second available study which examined volumetric grey matter changes related to SI combined cross-sectional and longitudinal designs (Babcock, 2015). Babcock compared brain volumes in a-priori defined ROIs in trainee interpreters and trainee translators before and after two years of training. In relation to the volumes of subcortical regions, this study revealed larger volumes of the right putamen and the right caudate nucleus in individuals who underwent interpreting training compared to trainee translators. An important distinction between these studies is that Elmer et al. investigated differences between highly experienced interpreters and highly experienced multilinguals, whereas Babcock compared trainee translators to interpreters in training, who had arguably less interpreting experience than the interpreters in Elmer et al.'s study. In this view, the larger caudate volumes in participants in Babcock's study may reflect ongoing optimisation of this structure as these participants were still trainees. In contrast, the significant negative effects of cumulative interpreting hours on the caudate volumes in fully trained interpreters in the Elmer et al.'s study suggest the caudate nucleus renormalisation after in the participants with consolidated interpreting skills.

Taken together, the existing evidence suggests that the roles of the caudate and the putamen are dissociated despite the importance of both structures in cognitive control and resolution of linguistic competition. The caudate appears to be of high relevance to all bilinguals, whereas the putamen's role appears to gain prominence in bilinguals who deal with rapid language switching, high demands of articulatory control, and simultaneity. Such a dissociation was also reported with respect to the differences in neural activation of these regions in various bilingual populations (Hervais-Adelman et al., 2015). It remains unclear, however, whether these differences would also translate distinctively into structural brain adaptations.

1.3. The current study

In this study we investigate volumetric characteristics of the caudate and the putamen among three groups of bilinguals with comparable language proficiency in a constant language pair (Czech-English), but who are expected to differ in terms of their bilingual experiences: highly experienced bilinguals, translators and interpreters. Based on DRM predictions and empirical findings, we expect that interpreters will have smaller volumes of both the caudate and the putamen than highly experienced bilinguals and translators. There is no available evidence on potential volumetric differences between bilinguals with translators. However, functional MRI studies suggest that translators fall between bilinguals and interpreters in terms of the intensity of relative activation of language-related regions in translating tasks (e.g., Van de Putte et al., 2018; for review see García, 2013). Therefore, we expect that their caudate nucleus and putamen volumes will also fall somewhere between these two groups.

Furthermore, we investigate the effects of bilingual experiences on the volumetric trajectories of the caudate nucleus and putamen. In contrast to previous studies, we focus on the general bilingual experiences which interpreters share with other groups of bilinguals and examine their relative brain structural effects for each of the studied groups. In doing so, we embrace the fact that interpreters, albeit at the extreme end of the bilingual experience, are still individuals with a wide variability in their bilingual experiences. Interpreting is only one of the bilingual experiences which is assumed to have effects on brain structure.

We capture the bilingual experiences with a composite score of *the Language Social Background Questionnaire* (LSBQ; Anderson et al., 2018b), which is a continuous measure of bilingual experiences. LSBQ has been also successfully used as a predictor of bilingualism-triggered brain adaptations in other studies (Anderson et al., 2018a; Aveledo et al., 2020; DeLuca et al., 2019a; Martínez-Horta et al., 2019; Pliatsikas, 2021). Using Bayesian Generalized Additive Mixed Models (BGAMMS), we examine both linear and non-linear trajectories of volumetric changes as predicted by bilingual experiences. We opted for Bayesian modelling because it will allow us to examine shapes of probable trajectories and their likelihood while not forcing us to make binary decisions based on p-values (Marra and Wood, 2012).

We expect to observe patterns of expansion-renormalisation of the caudate volumes in each of the groups, which may vary in shape and magnitude among the groups because of differences in their bilingual experiences. Based on studies on interpreters and the assumed superior bilingual control demands they exert in their jobs (García et al., 2020), we expect the caudate to show a steeper increase of the volumes in the less-experienced interpreters (i.e., interpreters with relatively lower LSBQ scores), as well as a steeper decrease in more experienced interpreters (i.e., interpreters with relatively higher LSBQ scores), compared to similarly experienced highly experienced bilinguals and translators. The pattern of expansion-renormalisation in the latter groups will be flatter, with milder increases and decreases in translators and still flatter effects in highly experienced bilinguals.

Finally, and following the suggestion of the NMSI (Hervais-Adelman and Babcock, 2020) that the putamen is a structure of particular importance for interpreters, we expect that if any experience-related renormalisation of putamen volumes is to be observed, this should be in interpreters. Conversely, we simply expect the putamen to increase with growing bilingual experiences in translators and highly experienced bilinguals.

2. Methods

2.1. Ethics statement

The research procedures in this study were approved by the Masaryk University Ethics Committee. Before taking part in the experiment, participants gave written informed consent and confirmed no contraindication to MRI scanning.

2.2. Participants

Three groups of native or native-like Czech speakers with a high command of English took part in the study: interpreters (n = 29, mean age = 35,7 y, SD = 7.26), translators (n = 37, mean age = 33 y, SD = 9.31), and bilinguals without professional experience (n = 47, mean age = 29.3 y, SD 7.68). Thus, in total we collected data from 113 participants (42 males; 71 females; mean age = 32 y, age range 18–53). Four participants did not complete the whole procedure (two highly experienced bilinguals, one interpreter, and one translator). Therefore, the final sample comprised of 109 participants: bilinguals without professional experience (n = 45), translators (n = 36), interpreters (n = 28). Information about the groups and their demographics can be found in Table 1.

Inclusion criteria comprised of right-handedness, normal or corrected-to-normal vision, indication of no history of neurological or language disorders, no contraindication to MRI, and all participants were required to hold a university degree or to participate in a full-time university education. The participants had comparable socio-economic status as indexed by their education and by education of their parents (at least one of the parents held a university degree). Because typological distance between the first and the second language has been reported to influence the cognitive control demands (González Alonso et al., 2020), we included only participants who were native speakers of a Slavic language. The majority of our sample had Czech as their native language (n = 105), whereby the other mother tongues were Russian (n = 4), Macedonian, Polish, Serbian, and Slovak (for each n = 1).

Additional inclusion criteria applied for specific groups. For the interpreters, participants needed to fulfil at least one of the following conditions: i. They were required to be court interpreters in language combination Czech-English in line with the Czech legal Act on Experts and Interpreters no. 36/1967 Coll. (Czechia, 1967); ii. They were required to be enrolled in the second year of the master's programme Interpreting for the language combination Czech-English at one of the two Czech universities offering certified interpreting training (i.e., Charles University or Palacky University Olomouc). This implied that they have obtained their bachelor's degree in Translation and Interpreting for the given combination, they have passed the highly selective entering exams for the master's degree in interpreting, and they underwent at least four years of simultaneous interpreting training.

To be included in the translators group, participants were required to fulfil one of the following conditions: i. They were needed to be court translators in the language combination Czech-English as stipulated by the Czech legal Act on Experts and Interpreters no. 36/1967 Coll. (Czechia, 1967); ii. They were supposed to be enrolled in the master's degree Translating for the language combination Czech-English. This programme is taught at three universities in Czechia (Charles University, Palacky University Olomouc, Masaryk University) and upon its completion, the students become court translators as specified in the relevant legal act; iii. They were Czech-English translators for living for at least four years on a weekly basis, whereby translating constituted the major source of their income.

To be included in the highly experienced bilingual group, besides the general criteria, participants were required not to practise translating and interpreting professionally. This meant that translating and interpreting should not have generated them income and that they should not have engaged in these activities more often than once a month.

Participants who had a mother tongue other than Czech were required to either hold the official Czech Language State Exam Certificate at the level C2 of the Common European Framework of Reference for Languages or an equivalent. All non-native Czech participants fulfilled this condition by being certified court interpreters or translators, which includes the examination of native-like level of Czech (Czechia, 1967).

Table 1
Mean (SD) of group demographics and LSBQ composite scores.

	Highly experienced bilinguals	Translators	Interpreters
N	45 (female 22)	36 (female 25)	28 (female 23)
Age (years)	29 (7.71)	32.42 (8.79)	35.68 (7.39)
LSBQ	4.30 (3.96)	6.14 (3.02)	5.87 (4.69)

All participants completed the online version of Lexical Test of Advanced Learners of English (LexTale) (Lemhöfer and Broersma, 2012) to assess that they meet the inclusion criteria of high English proficiency. The threshold for acceptance was set to level B2 or higher according to the Common European Framework of Reference for Languages (Council of Europe. Council for Cultural Co-operation. Education Committee. Modern Languages Division, 2001), which corresponds to 60% success rate or higher on the LexTale. According to the LexTale score, all participants were found to be highly proficient in English.

Participants also completed a Czech version of The Language and Social Background Questionnaire (Anderson et al., 2018b). This questionnaire gathers information about the demographics, code-switching practices, language background, history, language use and proficiency. An overall factor score calculator (Anderson et al., 2018b) synthesises information from the questionnaire into the LSBQ composite score of bilingual immersion. By using the LSBQ composite score, we obtained a measure of bilingualism as a continuous variable. We created a Czech version of this questionnaire (see Appendix C). The translation was created based on the English original. An independent researcher back-translated the Czech version to English, which was subsequently examined against the original. After the study was completed, the final questionnaire translation underwent a review by two Czech-English translators, who confirmed the adequacy of the translation and verified that the target text effectively conveys the same message as the source text. To determine group differences in LSBQ scores, ANCOVA with LSBQ as dependent variable and Age as covariate was run and revealed no significant effect of group [$F(2,109) = 2.63$, $p = .077$]. Post-hoc pairwise Bonferroni also did not reveal any significant between group differences (I vs. T: $p = 1$; I vs. B: $p = .29$; B vs. T: $p = .11$) The LSBQ scores for each group can be found in Table 1.

2.3. MRI data acquisition

MRI data collection took place at the Central European Institute of Technology (Brno, Czechia) using a 3T Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil. High-resolution T1 MPRAGE anatomical scans were collected with the following parameters: sagittal orientation, 256 slices, 0.7 mm isotropic voxels, acquisition matrix 246 × 256 mm, in-plane resolution 250 × 250, TE = 2.41 ms, TR = 2400 ms, inversion time 1140 ms, flip angle 8°. Data acquisition lasted approximately 10 min.

2.4. Data analysis

2.4.1. MRI data preprocessing

We preprocessed the T1-weighted images using the FSL_anat software pipeline (Jenkinson et al., 2012). We extracted the subcortical structures using the FIRST software pipeline (Patenaude et al., 2011). We automatically segmented left and right caudate nucleus and putamen. The segmentation was visually inspected for quality of extractions. We divided the volumes of the two regions by the brain volume. In doing so, we obtained the normalised brain volumes (i.e., proportional volumes which account for the head size differences). These proportional volumes were then submitted to the statistical analysis. The proportional volumes of the regions of interest are illustrated in Table 2. Values in all Tables and Figures are multiplied by 1000 for illustration purposes.

2.4.2. Caudate and putamen volumes - group differences

We investigated the group differences in the volumes of each ROI using Generalized Additive Mixed models (GAMMs) while controlling for non-linear effects of age. As we were not interested in comparisons of the trajectories, we opted for a frequentist approach. Data were analysed in R (R Core Team, 2019) using gam() function of the mgcv package

Table 2
Proportional volumes (m^3) of the two regions of interest.

Mean proportional volumes (SD)				
group	left caudate nucleus	right caudate nucleus	left putamen	right putamen
bilinguals	2.60(0.20)	2.66(0.28)	3.36(0.26)	3.28(0.27)
interpreters	2.69(0.23)	2.69(0.29)	3.45(0.22)	3.40(.19)
translators	2.72(0.23)	2.79(0.28)	3.43(0.23)	3.39(0.27)
Total	2.67(0.22)	2.71(0.28)	3.41(0.24)	3.36(0.24)

(Wood, 2011a). GAMs operate on a principle of non-linear regression splines which are computed as the sum of simpler non-linear functions for each of the fitted variables. Note that the introduction of non-linearity into the model mathematically penalizes the estimated model fit. We used the method of Restricted Maximum Likelihood (REML, Wood, 2011a) which computes the trade-off between the distance of the fitted line from the residuals and the penalised non-linear splines. Therefore, the non-linear splines are fitted only when the fit of a curved function subtracted by its penalty outweighs the fit of a linear regression spline. If REML gives favour to a linear regression spline, the results can be interpreted as from Generalized Linear Mixed Effects models. For both ROIs, we fitted regression splines for the main effects of Group and Hemisphere, a smooth term of Age, together with Participant and Gender as random effects.

2.4.3. Effects of bilingual experiences on brain volumes for each of the tested groups

To test the effect of bilingual experiences on the volumes of ROIs for each group, we used Bayesian Generalized Additive Mixed Models using software R (R Core Team, 2019), stan_gamm4() function of the *rstanarm package*, version 2.21.1 (Goodrich et al., 2020). Bayesian modelling allows for direct testing of the research hypothesis, compared to the frequentist statistics which allows only for rejection of the null hypothesis. Thus, the use of this method allows us to obtain the probability of a bilingual experiences having dynamic effect on volumes of the putamen and the caudate. In Bayesian inference, such probabilities are called posterior probabilities, or posteriors, because they are computed after the data have been taken into account. They also depend on prior probabilities, or priors, which represent the researcher's prior beliefs in the probability of some parameters before the data are taken into account. The current study is the first one to test effects of bilingual experiences on similar populations. Therefore, we used the default weakly informative priors of the native to the R package *rstanarm*, which help to constrain the posteriors to reasonable values and help stabilize computation as generally recommended by Wood (2017). The priors for each model are to be found in Appendix D. Bayesian GAMMs allowed us to study a continuum of credibility of assumed effects without forcing us to make binary decisions based on p-values.

To specify whether the Bayesian GAMMs should be fitted for each hemisphere separately, we used frequentist Generalized Additive Mixed Models to estimate whether the effects of LSBQ in both Hemispheres were significantly different, which would prompt us to split our data according to hemisphere. We applied an analytical procedure in accordance with the "vibration of effects" approach (as per Korenar et al., 2023a). We fitted six GAMMs with main effect Age and LSBQ × Hemisphere interaction for each group and in both structures. Each model was run twice with both levels of ordered factors of Hemisphere as the reference level. For no group or structure did the LSBQ × Hemisphere interaction emerge as significant in both relevant versions of the models with different reference levels (see Appendix B for the results of this procedure). Therefore, we did not fit separate Bayesian models for each hemisphere and averaged the grey matter volumes across both hemisphere in our regions of interest.

We fitted three Bayesian Generalized Additive Models for both ROIs, one for each of the investigated groups. The response variable were the normalised volumes of caudate and putamen. We treated our main predictor LSBQ as a main effect together with Age and Hemisphere, and Subject as a random effect. The algorithm was set to compute 4000 posterior estimates that make up our posterior distribution (1000 estimates in four Markov chains per each model), with additional 1000 estimates for each chain which are used for the warm-up of the model.

2.4.4. Assessing model fits using posterior predictive model checks

We checked the posterior predictivity of our models using the estimated posterior distributions made up with the 4000 iterations (as per Levshina, 2018). Because the predicted values are generated based on the variables we submitted to our models, the values form a distribution of what the values should look like under the condition that the hypothesised models are correct. In all, the model fits were assessed using R^2 posterior distributions and posterior distribution of the estimated values to confirm that the distribution of the observed data fall within distribution of predicted estimates (Muth et al., 2018).

3. Results

3.1. Volumetric group differences and the effects of age

Fig. 1 illustrates the results of the analyses of volumetric group differences while taking age into consideration, using GAMMs. The results revealed a significant main effect of Group on caudate volumes (p = .013) and putamen volumes (p = .01). Highly experienced bilinguals had significantly smaller volumes of the caudate compared to both translators (p = .004) and interpreters (p = .048). Furthermore, bilinguals were also found to have significantly smaller volumes of the putamen than translators (p = .024) and interpreters (p = .005). There were no significant differences between translators and interpreters in the volumes of the caudate nucleus (p = .558), or the putamen (p = .412). Age emerged as a significant predictor for the caudate nucleus ($p < .001$), with volumes decreasing with older age. A similar relation did not reach significance for the putamen (p = .088), but there was a downward trend.

Group differences of the normalised grey matter volumes (y-axes) of the caudate nucleus (left) and putamen (right) collapsed across hemispheres as a function of age (x-axes). Significant group differences in both regions: Bilinguals (i.e., highly experienced) vs. Translators; Bilinguals vs. Interpreters.

3.2. Effects of quantified bilingual experiences on regional brain volumes

Based on the R2 posterior distribution, which conclusively demonstrated that the effect of our main predictor in all the models is nonzero (refer to section 3.3 and Fig. 1), we decided to determine the credibility intervals by visually inspecting the plots, following the approach by Levshina (2018) to assess their width. Bayesian credible intervals (CI) offer estimations of the parameter of interest through the use of the computed posterior distribution, which integrates all existing knowledge and evidence regarding the population distribution. When interpreting the Bayesian 95% CI, it implies a 95% probability that the true (unknown) effect estimate falls within the interval, taking into account the evidence derived from the observed data (Hespanhol et al., 2019).

The effects of bilingual experiences as measured by LSBQ on the volumes of the caudate nucleus and putamen are shown in Fig. 2, separated by group. For interpreters, the relationship between quantified experiences and volumes of the caudate nuclei and putamen followed an inverted U-shape. Specifically, with increasing levels of bilingual experiences, volumes of both the caudate nucleus and putamen were shown to increase first, and to decrease after a certain level of bilingual experiences had been reached. Notably, the extent of bilingual experiences after which the renormalisation occurs is higher for putamen than for caudate.

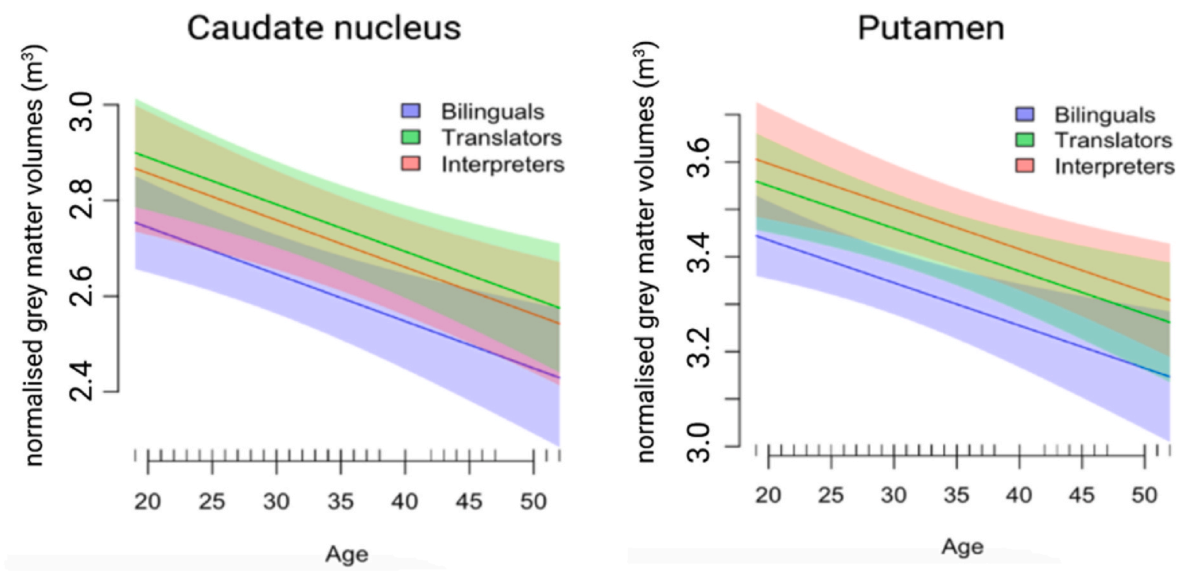

Fig. 1. Group differences and the effects of age on the normalised volumes of the ROIs.

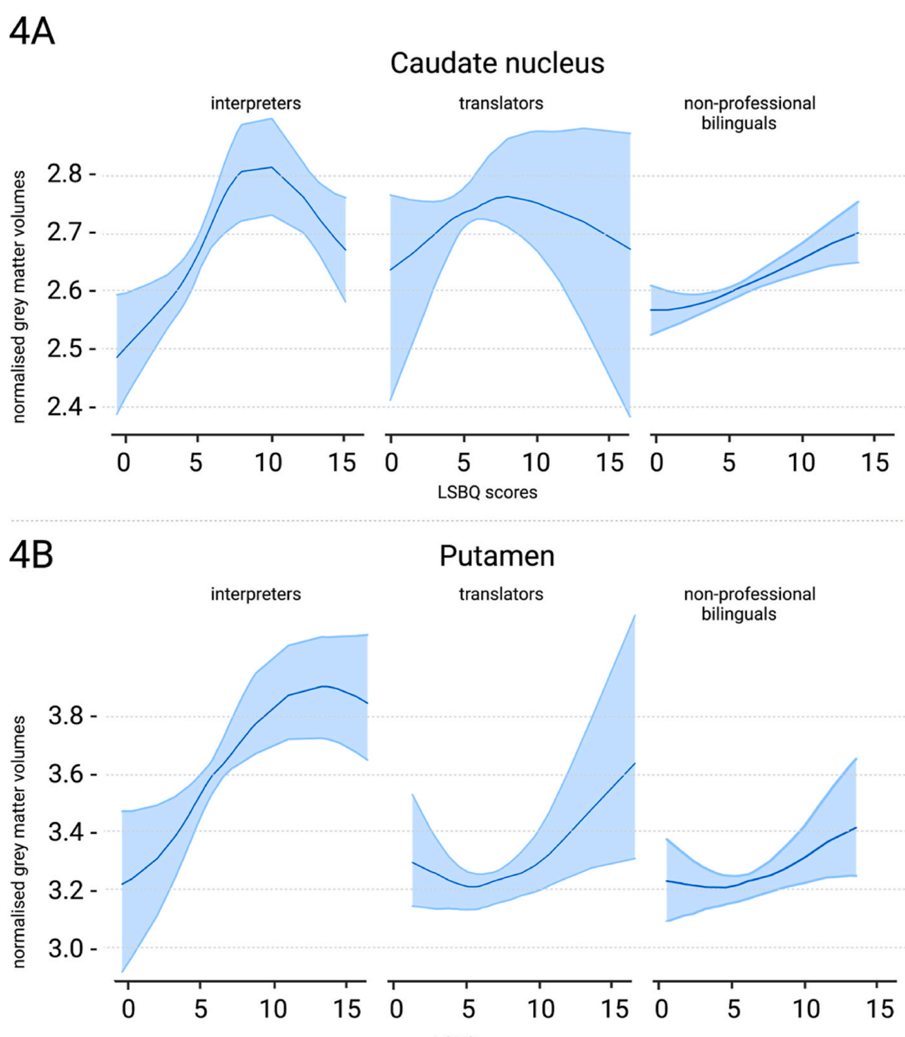

Fig. 2. Estimated effects of LSBQ scores on the normalised volumes of ROIs.

For translators, effects of bilingual experiences on the putamen revealed a non-linear positive pattern of volume increase with increasing bilingual experiences. Furthermore, the results indicate that bilingual experiences are linked to a mild increase of caudate volumes in less experienced translators (i.e., translators with relatively lower LSBQ scores) with mild decreases in more experienced ones (i.e., translators with relatively higher LSBQ scores). These effects are weaker than those found in interpreters, as indicated by the flatness of the curves, and the broader confidence bands.

The relation between LSBQ scores and ROI volumes in highly experienced bilinguals revealed that caudate and putamen volumes are positively predicted by bilingual experiences, with a shape of an upward opening parabola. The slope depicting the positive effect was steeper for the caudate than for the putamen.

Estimated effects of LSBQ (x-axes) scores on the normalised volumes of the caudate nucleus (4A) and putamen (4B) in interpreters (left), translators (middle), and highly experienced bilinguals (right). The side-by-side setting of the plots for each group was performed manually *(Created with Biorender.com)*.

3.3. Results of the model fits' assessment

We assessed the posterior distribution of R^2 statistics of the 4000 iterated models, as well as the credible intervals within which 95% of the posterior distributions lies, shown in the histograms in Fig. 3. These intervals indicate the range between the 2.5% and 97.5% percentiles, encompassing the central 95% of the posterior distribution. In essence, credible intervals represent the most plausible values for the posteriors. In situations where a categorical judgment is necessary, such as determining whether a variable influences the likelihood of a particular outcome, this criterion can be employed (Levshina, 2018). If the credible interval excludes zero, it signifies a credibly nonzero effect. Our posteriors explain on average above 57% of the variance in volumes of caudate and putamen. As none of the credible intervals include zero, the effects of predicting variables in our models are credibly nonzero. The posterior distribution also offers a means to evaluate the likelihood of observing positive and negative effects of the LSBQ scores on grey matter volumes of the regions under study. This is achieved by calculating the proportions of the posteriors that are greater and less than zero. As evident from Fig. 3, the proportion of posteriors greater than zero is 100%. This information allows us to directly test the alternative hypotheses of the effects of LSBQ on the grey matter volumes. In other words, in the context of Bayesian probabilistic testing, these tests indicate a high likelihood that the hypothesised models are correct and allow us to directly examine the estimated effects of our models. Moreover, we evaluated how well the models fit our data by comparing the predicted values for all iterations to the actual values. The observed data fall into fields of the predicted data distributions, which indicates good model fits, as illustrated in plots in Appendix A.

R^2 values (x-axes) of the predicting variables in the investigated models on the volumes of caudate (upper band) and putamen (lower band) in the three groups under study. Red lines depict the credibility interval wherein lies 95% of estimated R^2 means. The red dot depicts the R^2 of the collected data. CI: credibility intervals expressed numerically *(Created with Biorender.com)*.

4. Discussion

This structural MRI study investigated bilingualism-induced structural brain plasticity related to general and professional bilingual experiences in interpreters, translators, and highly experienced bilinguals. Specifically, we examined between-group comparisons with respect to the volumes of the caudate and the putamen, two subcortical structures with crucial roles in handling two languages. Moreover, we used a continuous measure of general bilingual experiences, the LSBQ score, as a predictor of non-linear volumetric trajectories in the ROIs for all three groups by using Bayesian Generalized Additive Mixed Models. Overall, this study aimed to shed new light on structural brain adaptations induced by strenuous and sustained cognitive challenges.

Our between-group comparisons revealed that our two groups of professional bilinguals had larger volumes of the caudate nucleus and the putamen than highly experienced bilinguals, with no differences

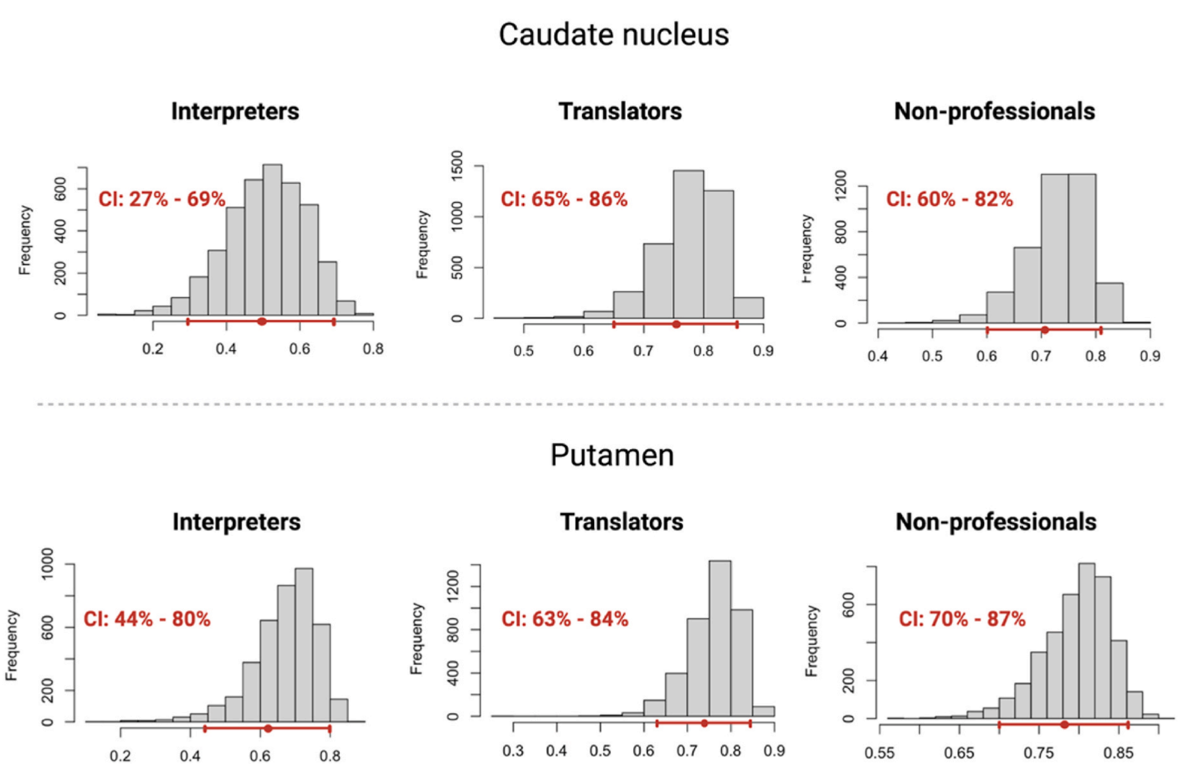

Fig. 3. Posterior probability distribution of the R^2 values.

observed between translators and interpreters. Furthermore, we observed that quantified bilingual experiences predict volumetric adaptations in both regions for all our groups. Notably, our results revealed that these adaptations follow dynamic trajectories that vary in shape and intensity among the three bilingual groups under investigation. We will further discuss the importance of these results for broadening our understanding of bilingualism-induced neuroplasticity in the context of previous studies and relevant theories.

Our finding of larger volumes of the caudate nucleus and putamen in professional bilinguals relative to highly experienced bilinguals is consistent with the view that increased and sustained language control demands can result in larger grey matter volumes in the basal ganglia (Burgaleta et al., 2016; Pliatsikas et al., 2017). In this view, larger caudate and putamen volumes in interpreters and translators compared to highly experienced bilinguals would reflect increased demands for control of two languages related to their professions. Importantly, these effects emerged when compared to a bilingual control group, not to the usual monolingual groups used in previous studies, showing that structural effects of bilingualism may still exist but differ among bilingual groups with different experiences. However, this finding is in contrast with two existing studies on volumetric group differences in similar samples which were also compared to non-monolinguals. Specifically, one study reported that highly experienced interpreters did not have significantly different caudal volumes compared to multilinguals (Elmer et al., 2014) while the other study showed that novice interpreters had larger caudate and putamen volumes compared to novice translators after two years of training (Babcock, 2015). This discrepancy can be attributed to methodological differences between the studies, including the segmentation methods of the structural MRI images, different statistical approaches, and the substantially smaller sample in Elmer et al. (2014). Another difference between the current study and Elmer et al. was that the former kept the language pair constant, whereas participants in the latter had a variety of language pairs. In this view, the two studies differed in the relative typological language proximity, which can have variable effects on cognitive resources needed to support successful control for two languages (Rothman, 2015), and as such can lead to different structural effects (Lee, 2022). Moreover, the samples in the three studies likely differed in the range of professional experiences among the subject groups; the current study and Babcock (2015) included also interpreting trainees in the last phase of their education, whereas Elmer et al.' study investigated only fully trained interpreters. Overall, this highlights the importance of assessing bilingual experiences on a continuum when determining their structural effects on the brain as argued in existing models of bilingualism-induced neuroplasticity (i.e., DRM).

We will now discuss the follow up analysis in which we directly addressed the issue of how quantified bilingual experiences affect the putamen's and caudate nucleus's volumetric adaptations and their trajectories within each group. The trajectory of the volumetric changes observed in the caudate nucleus appears typical of the expansion-renormalisation trajectory (Wenger et al., 2017). Specifically, with growing bilingual experiences in interpreters, the trajectory is consistent with increases of volumes of the caudate nucleus. With even higher LSBQ scores, volumes of this structure appear to decrease. This finding is line with the only existing study which related volumes of caudate to interpreting experiences and reported that hours of interpreting practice negatively predicted caudate volumes (Elmer et al., 2014). Taken together, these findings suggest that sustained and extreme involvement in bilingual language control leads to eventual decreases (renormalisation) of caudate nuclei's volumes, a pattern that has been proposed for experienced bilinguals in general (Pliatsikas, 2020).

A similar pattern of expansion-renormalisation of the caudate nucleus was also partially observed in translators. However, the trajectories in the two groups of professional bilinguals are distinct in terms of the steepness of observed increases in the first half of the slope and levels of renormalisation in the second half of the slope (i.e., part of the trajectory depicting individuals with exceptionally high experiences). In other words, despite the expansion-renormalisation pattern having been observed in both professional groups, the trajectory revealed here suggests there are notable differences between translators and interpreters with respect to the trajectory of the volumetric changes of the caudate nucleus, and that these are related to differences in bilingual experiences. Interestingly, level of *general bilingual experiences* of translators were highly comparable to those of interpreters. The differences between our groups can be likely ascribed to the differences in their professional bilingual practices as all the groups are assumed to use their two languages qualitatively differently. In this paper, we approached the anticipated qualitative disparities in bilingual language use among the groups as an indicator of how the quality of bilingual experiences can influence the grey matter properties, extending beyond mere quantitative measures (as assessed through LSBQ composite scores). In this view, the results presented here suggest that bilingual practices common to all bilinguals have measurable effect on the regional brain volumes, but such effects are further conditioned by the qualitative differences in bilingual practices beyond general bilingual experiences. This warrants a further investigation on relative contribution of both *general* and *professional* bilingual practices on the brain structure.

In contrast, in highly experienced bilinguals, growing bilingual experiences emerged as clear positive predictor of the volumes of the caudate nucleus. This was not expected, as we hypothesised caudate to decrease in highly experienced bilinguals within all the groups investigated here. Recall that this prediction was based on the hypothesis that the caudate subserves bilingual control processes important for all bilinguals, as larger volumes were reported even in individuals at the beginning of bilingual language acquisition, and smaller volumes were reported in highly proficient bilinguals who did not necessarily undergo any formal professional training (Pliatsikas et al., 2017). One possible explanation for this discrepancy is that the highly proficient group investigated here, did not have enough opportunity for immersion in bilingual language use. That is, they were Czech native(-like) speakers living in Czechia, which is a highly monolingual country. By contrast, the sample of Pliatsikas et al. (2017) consisted of bilinguals who were highly immersed in an environment where the dominant language was not their native one, but who often continued using their first language.

As for the putamen, its volume followed an expansion-renormalisation trajectory in interpreters only, which was in line with our predictions. In translators and highly experienced bilinguals, the slope is suggestive of a positive relationship between bilingual experiences and grey matter volumes of this structure. Recall that the putamen subserves processes which have been assumed to be continuously required by interpreters, such as rapid language switching, articulatory control, and control for simultaneously executed processes (Hervais-Adelman et al., 2015).

The caudate nucleus and the putamen have been proposed to be at the core of the NMSI model which also posits a functional dissociation of these two regions (Hervais-Adelman and Babcock, 2020). With respect to the current study, the putamen renormalised only in interpreters who, according to the NMSI, rely on its functionality more intensely than other bilinguals (Hervais-Adelman et al., 2015). In contrast, the renormalisation of the caudate nucleus was observed in interpreters and translators. This suggests that the functional dissociation of these structures observed in previous studies and posited in the NMSI was replicated on a structural level in the current study.

Our findings also corroborate and extend the Dynamic Restructuring Model (DRM). The DRM proposes that structural brain adaptations brought about by bilingualism are dynamic *and* systematic, and that the systematicity can be revealed if the observed structural effects are viewed as a consequence of the intensity, timing and type of the bilingual experiences which cause them. The observed renormalisation of the caudate nucleus and the putamen in interpreters supports the hypothesis from the DRM that relevant brain structures in interpreters will eventually decrease due to the optimisation to the long-standing involvement in unprecedentedly intense bilingual language control they face in their professions. This is significant because predictions of the DRM with respect to extremely experienced bilinguals were based on very limited existing evidence. Moreover, only utilisation of methods which can reveal non-linear relationship, as used here, could test predictions of the dynamic effects on brain structure directly. The differences in the extent to which the relevant structures increase and decrease in volume across groups observed here also support the DRM's notion that the intensity of bilingual experiences can bring about a measurable distinction in the magnitude of these effects.

Note that we based the differences between translators and interpreters discussed above on the estimated trajectory of subcortical changes, not the average volumes. In point of fact, the mere analysis of group differences between translators and interpreters in the regional brain volumes did not emerge as significant. However, our more nuanced analysis using continuous predictors of bilingual experiences revealed distinct qualitative differences between the volumetric trajectories in these two groups. To our knowledge the only existing study which used a bilingualism-related continuous predictor of volumetric brain changes in interpreters was that of Elmer et al. (2014), who used cumulative hours of interpreting practices to reveal grey matter adaptations. However, this measure is specific to interpreters, which prevents comparison of experience-related neuroanatomic effects across groups.

The relevance and impact of the current study should be evaluated against its possible limitations. First, since we did not collect information about cumulative hours of engagement in professional bilingual practices, direct comparisons of the current findings with existing studies are limited (Elmer et al., 2011, 2014). Using hours of translating and interpreting practice as a covariate and the LSBQ score as main predictor on brain volumes will make it possible to distinguish between the neural effects caused by interpreting or translating, and those caused by experiences common to all bilingual groups. We acknowledge that we did not conduct a qualitative assessment of the translating and interpreting skills among the participants in our study sample. This aspect represents a crucial avenue for future research, as it holds the potential to enrich and expand upon the current findings.

Another potential limitation pertains to the possible effects of knowledge of additional languages on brain structure (i.e., the effects of knowing languages other than Czech and English). In our study, we considered the effects (indexed by LSBQ scores) of the use of two languages only, which is an approach common in studies in the field (e.g., Anderson et al., 2018a; Deluca et al., 2019b; DeLuca et al., 2020, but see Hervais-Adelman et al., 2018). However, we maintain that the current study already provides a more homogenized sample concerning language profiles compared to other studies on translators and interpreters (e.g., Elmer et al., 2014; Klein et al., 2018; Van de Putte et al., 2018). We deliberately maintained the language pair in which the participants interpret and translate constant (Czech and English). Additionally, we ensured relative consistency in the participants' L1 and L2, both being Slavic languages and English. This deliberate approach sets our study apart from others in the field, which often include various language combinations for interpretation and L1 and L2 with typologically different languages. Nonetheless, the data as presented here could have been impacted by the multilingual practices of the sample under study. To address this limitation, future studies should use additional tools beyond LSBQ to gather comprehensive information about participants' knowledge and use of all languages they are proficient in, beyond just their L1 and L2.

Furthermore, we opted for a Bayesian analysis, which is particularly powerful when informed by priors, i.e., previous observations before the actual model is computed. However, in the absence of any studies with comparable methodologies and samples, we could not integrate prior distributions. Therefore, we informed our model about the ranges of possible values by using weakly informative priors (as per Kruschke, 2011), which is a common practice when any previous results on comparable populations are absent. This method has been successfully applied in previous studies (e.g., Haendler et al., 2020; Levshina, 2018; Williams et al., 2018). Nevertheless, this constitutes an important step forward in the field, allowing future studies to leverage the current data set for the creation of highly informative priors. Furthermore, in future studies combining structural data with cognitive tasks may shed more light on how the groups under study differ in their cognitive abilities, and whether these differences contribute to the structural brain differences observed here.

4.1. Conclusion

Our study provides new insights into how sustained and exceptionally demanding bilingual experiences affect structural adaptations in the caudate nucleus and putamen in interpreters, translators and highly experienced bilinguals. Our results reveal that general bilingual experiences have dynamic, non-linear effects on the caudate nucleus and the putamen depending on the quantity of the accumulated experiences, and that the volumetric trajectories triggered by these experiences are group-specific. Overall, the current findings underline the importance of assessing general bilingual experiences on a continuum when investigating neural correlates of bilingualism. Also, the dynamicity of the effects observed here call for further use of methods which can model non-linear relationship between behaviour and brain changes. By and large, the application of these approaches and the study of neuroplasticity in bilinguals with exceptional bilingual experiences, such as interpreters, can elucidate the extent to which our brain can adapt when facing even the most arduous cognitive challenges.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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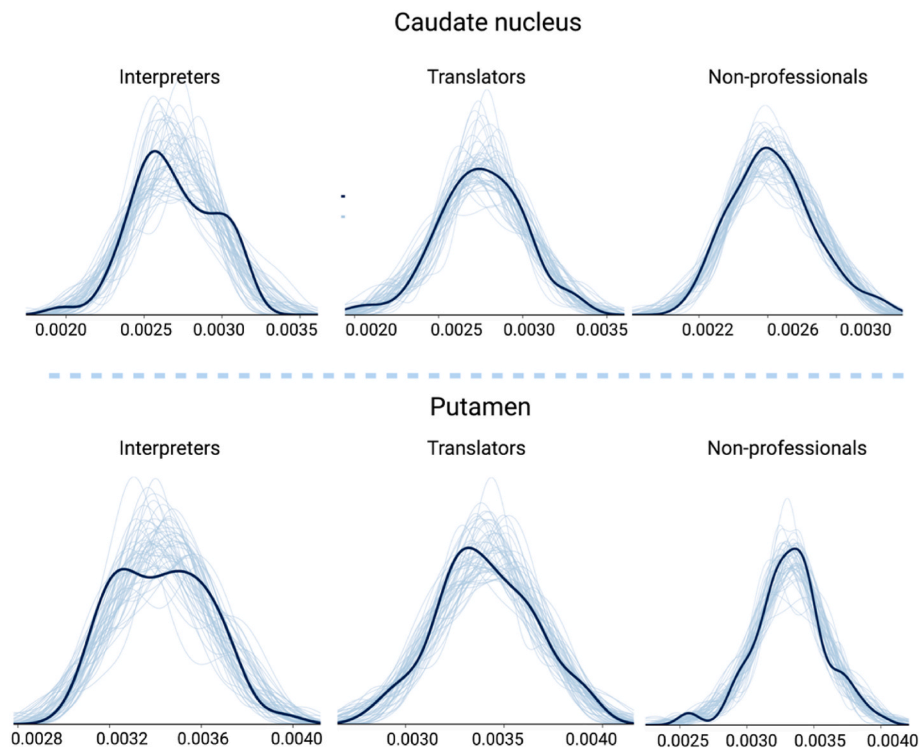
Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.amper.2023.100148.

APPENDICES.

Appendix A. Assessing the model fits by the visual overlay of the data estimated during 4000 iterations and the distribution of the observed data



Appendix A. Overlay of data distributions from 4000 model iterations and the actual observed data.
The light blue lines represent the distributions of the predicted values from each of the 4000 iterations. The dark blue line depicts distribution of the observed data. (x-axes: value of the normalised volumes of caudate and putamen, y-axes: frequency of the observed value)
(Created with Biorender.com)

Appendix B. Estimation of effects of LSBQ in each hemisphere; LSBQ × Hemisphere interaction

The following tables show *p*-values from six GAMMs, using the function *gam()* as implemented in the *mgcv* package (Wood, 2017) in the statistical software *R* (R Core Team, 2019) as results from the analytical procedure in accordance with the "vibration of effects" (as per Korenar et al., 2022). The results feature separate tables for each group and in both structures, while the variables submitted to this procedure included main effect *Age* and *LSBQ* × *Hemisphere* interaction. Each model was run twice with both levels of ordered factors of Hemisphere as the reference level (i.e., the columns *Left* and *Right)*.

CAUDATE – HIGHLY EXPERIENCED BILINGUALS		
Reference level of Hemisphere	Left	Right
Age	0.005	0.008
LSBQ x hemisphere	0.021	0.412
CAUDATE – TRANSLATORS		
Reference level of Hemisphere	Left	Right
Age	0.074	0.137
LSBQ x hemisphere	0.181	0.116
CAUDATE – INTERPRETERS		
Reference level of Hemisphere	Left	Right
Age	0.072	0.125
LSBQ x hemisphere	0.029	0.889
PUTAMEN – HIGHLY EXPERIENCED BILINGUALS		
Reference level of Hemisphere	Left	Right
Age	0.006	0.007
LSBQ x hemisphere	0.372	0.907
PUTAMEN – TRANSLATORS		
Reference level of Hemisphere	Left	Right
Age	0.213	0.213
LSBQ x hemisphere	0.882	0.787

(*continued on next page*)

(*continued*)

PUTAMEN – INTERPRETERS		
Reference level of Hemisphere	Left	Right
Age	0.02	0.021
LSBQ x hemisphere	0.061	0.914

Appendix D. The default priors used for each Bayesian GAM

The priors in *rstanarm* package of R are not flat; instead, they are intentionally designed to be weakly informative. These default priors offer moderate regularization, which aids in stabilizing computations. To achieve weakly informative priors, *rstanarm* internally adjusts the scales of the priors. The provided data has been generated using the function *prior_summary()* (Brilleman et al., 2020).

1. Priors for model depicting the effects of LSBQ on volumes of the caudate nucleus in interpreters:

   Intercept (after predictors centered)
   location = 0.0027, scale = 0.00065
   Auxiliary (sigma)

   ~ exponential(rate = 3838)
2. Priors for model depicting the effects of LSBQ on volumes of the caudate nucleus in translators:

   Intercept (after predictors centered)
   location = 0.0028, scale = 0.00064
   Auxiliary (sigma)

   ~ exponential(rate = 3922)
3. Priors for model depicting the effects of LSBQ on volumes of the caudate nucleus in bilinguals

   Intercept (after predictors centered)
   location = 0.0026, scale = 0.00061
   Auxiliary (sigma)

   ~ exponential(rate = 4120)
4. Priors for model depicting the effects of LSBQ on volumes of the putamen in interpreters:

   Intercept (after predictors centered)
   location = 0.0034, scale = 0.00052
   Auxiliary (sigma)

   ~ exponential(rate = 4842)
5. Priors for model depicting the effects of LSBQ on volumes of the putamen in translators:

   Intercept (after predictors centered)
   location = 0.0034, scale = 0.00062
   Auxiliary (sigma)

   ~ exponential(rate = 4039)
6. Priors for model depicting the effects of LSBQ on volumes of the putamen in bilinguals

   Intercept (after predictors centered)
   location = 0.0033, scale = 0.00066
   Auxiliary (sigma)

   ~ exponential(rate = 3764)

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