Running header: **Neural correlates of code-switching practices**

Full title: **Structural neural correlates of habitual code-switching practices in bilinguals***

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Abstract

Bilingualism impacts brain structure, especially in regions involved in language control and processing. However, the relation between structural brain changes and key aspects of bilingual language use is still poorly understood. Here we used structural MRI and non-linear modelling to investigate the effects of habitual code-switching (CS) practices on brain structure among Czech-English bilinguals. We studied the effects of usage frequency of various CS types (categorised by directionality and level of language separation) on the volumes of the caudate nucleus and the thalamus. Volumes of caudate nuclei were positively correlated with overall CS frequency, with stronger effects for switches from L1 to L2. Thalamic volumes were positively correlated with engagement in forms of CS for which the two languages are more separate, with stronger effects for switching from L2 to L1. These results underscore the importance of using detailed measures of bilingual experiences when investigating the sources of bilingualism-induced neuroplasticity.

Keywords: bilingualism; code-switching; structural neuroplasticity; grey matter volume; thalamus; caudate nucleus

1. Introduction

The key cognitive challenge for bilinguals is to use only one language at a time although both languages are simultaneously active in their brain (Blanco-Elorrieta & Caramazza, 2021; Hanulová et al., 2011; Kroll & Bialystok, 2013; Kroll & Chiarello, 2016; Marian & Spivey, 2003). Therefore, beyond the acquisition of a second linguistic system, bilinguals must continuously monitor the communicative circumstances and selectively use one of their languages while suppressing the other. This constant monitoring and suppression confer increased cognitive demands on neural systems involved in language processing and cognitive control (Kroll et al., 2012). Our brain structure supports the use of the repertoire of thinking processes and behaviours necessary to achieve our everyday goals (Wenger & Kühn, 2021). However, the language processing and cognitive control linked to bilingualism have been shown to be so demanding that they stretch functional needs beyond the limits of existing neural resources. In turn, the brain adapts its structure to support the functional repertoire required to meet the new demands, relying on neuroplasticity (Kroll & Chiarello, 2016). In general, experience-induced structural adaptations occur in the neural circuits which subserve the task at hand (Kleim & Jones, 2008; Lövdén et al., 2020). In line with this, bilingualism has been shown to induce structural brain changes in areas subserving cognitive control and language processing (Pliatsikas, 2020). However, findings on bilingualism-induced brain changes have not been consistent, with studies reporting both increases and decreases of volumes in a variety of brain regions (Pliatsikas, 2020). This has led some researchers to query whether the reported effects are reliable (García-Pentón et al., 2016), and even whether there are any robust effects of bilingualism on neurocognition at all (see for a recent overview Leivada et al., 2021).

However, inconsistencies are perhaps not surprising given that bilingualism is a fundamentally heterogeneous phenomenon comprising a range of experience-based factors (Bak, 2016; Bialystok, 2016; Green & Abutalebi, 2016; Luk & Bialystok, 2013). Studies focusing on individual differences in bilingualism-related factors such as language proficiency, the onset of second language acquisition, proportionality of the use of both languages, and duration of second language use have made it possible to provide further insights into the differential structural changes related to bilingualism (DeLuca et al., 2019; Fedeli et al., 2021; Gullifer & Titone, 2020; Stein et al., 2014). Yet, the effects of other aspects of bilingual language use on brain architecture, such as habitual language switching practices, are still poorly understood. The apparent inconsistency in findings can, in part, be ascribed to the

experimental tasks that were used. Previous studies investigating bilingualism effects on brain and cognition often relied on tasks with low granularity, test-retest reliability, and ecological validity (Blanco-Elorrieta & Pykkänen, 2018; Karalunas et al., 2020; Rey-Mermet et al., 2018). This has rightfully prompted the question whether such measures can really tap into the cognitive control required in bilinguals' everyday lives (Leivada et al., 2021). While achieving high ecological validity in an experimental setting is challenging, it is nevertheless important to strive for the ecologically most valid stimuli possible, as this aspect has been shown to substantially impact results (Blanco-Elorrieta & Pykkänen, 2017).

Taken together, to further advance our understanding of how bilingualism gives rise to structural changes, we need to look at code-switching, that is a bilingual behaviour which has been largely overlooked as a subject of neuroscientific studies. Specifically, we aim to identify the brain structural effects of the different types of code-switching using a task containing authentic code-switching sentences.

1.1 Code-switching

Code-switching is the ability to alternate between two languages between or even within sentences, e.g., in the following Czech sentence containing English words: *Tady vidíš, že ona je in need a potřebuje entertainment.* ("Here you see that she is in need and needs entertainment") (Myslín & Levy, 2015, p. 872). Notably, evidence shows that this behaviour comes with cognitive costs as indicated by observations of a slow-down of speech rate in producing code-switched sentences compared to monolingual sentences (Costa & Santesteban, 2004; Faroqi-Shah & Wereley, n.d.; Fricke et al., 2016), as well as longer naming and reading times in trials where the language of use is changed compared to trials where it is not (Altarriba et al., 1996; Gollan & Ferreira, 2009; Linck et al., 2013; Meuter & Allport, 1999, but see Gullifer et al., 2013). Furthermore, EEG recordings during a sentence comprehension task reported a larger N400 component for sentences involving code-switched words, indexing switching costs related to lexico-semantic access and integration (Christoffels et al., 2007; van Hell & Witteman, 2009).

1.2 Code-switching and cognitive control

Why does code-switching come with cognitive costs? Code-switching can involve copious switching between languages within one conversation and even within a single sentence (Green, 2018). This presupposes a constant involvement of cognitive control

processes such as monitoring and inhibition (Costa et al., 2009). Monitoring enables bilinguals to choose the appropriate language and trigger a switch if the circumstances require it, and inhibition allows for the suppression of one of the languages in rapid succession (Blanco-Elorrieta & Caramazza, 2021).

The processes described above suggest that code-switching is a cognitively demanding form of language behaviour, although not all forms of code-switching are equally costly. Cognitive costs may differ, for example, depending on switching *directionality*. Specifically, compared to L1-L2 switches, switching from L2 to L1 has been consistently associated with higher cognitive demands as indexed by slower naming latencies (for review, see Bobb & Wodniecka, 2013). Moreover, electrophysiological studies often report ERP patterns suggestive of increased difficulty when switching from the weaker L2 to the dominant L1 (for review, see van Hell & Wittenman, 2009). These findings suggest that suppressing the dominant language to facilitate the less dominant one requires more inhibitory control than vice versa (Levy et al., 2007; Linck et al., 2009; Wodniecka et al., 2020), which in turn makes subsequent reactivation of the dominant language harder (Green, 1998).

Besides directionality, another factor by which code-switching may engage cognitive control processes to various degrees is the *level of separation* between the two languages within a switch (Green & Wei, 2014; Hofweber et al., 2016, 2020b; Treffers-Daller et al., 2020). The primary distinction is whether a switch occurs *within* one sentence which features lexical units and grammatical elements from both languages (*intrasentential* code-switching) (Treffers-Daller, 1991) or *after* a sentence has been completed (*intersentential* code-switching) (Appel & Muysken, 2005). Intersentential code-switching has been associated with higher inhibitory control than intrasentential code-switching (Gollan & Ferreira, 2009; Kuzyk et al., 2020), owing to the need to more strongly suppress the unwanted language in the former than in the latter.

The Adaptive Control Hypothesis (ACH, Green & Abutalebi, 2013) offers an explanation for the differences between cognitive control levels linked to the degree of separation of two languages. According to the ACH, the degree of inhibitory control is partly determined by the interactional context in which bilinguals operate. Code-switching occurs in two interactional contexts, which differ in the typical degree of separation of both languages. In the *dual-language context*, bilinguals typically use one of the languages at a time, while both languages remain activated to allow for a switch to a different conversation partner. This situation comes with high inhibitory control demands. Code-switching in this context typically

does not occur within one sentence but only intersententially. On the other hand, intrasentential code-switching occurs in the *dense code-switching context* in which bilinguals can mix both languages freely, even within one sentence. This would require high monitoring skills to handle linguistic co-activation, but less inhibitory control, as both languages need to remain highly activated. The hypothesis central to the ACH that the dual-language context requires more inhibitory control than the dense code-switching context has been corroborated by several psycholinguistic studies (Beatty-Martínez et al., 2019, 2020). However, the ACH does not differentiate between different types of intrasentential code-switching occurring within the dense code-switching context, which themselves may rely on inhibitory control processes to different degrees. As it is likely that paying more attention to these typological differences in code-switching behaviour can help resolve conflicting findings in the literature, we turn our attention to these differences in the current study.

Muysken (2013) proposed a typology of intrasentential code-switching types based on the level of separation between two languages. Muysken defined three types of code-switching, listed here in descending order of language separation: alternation, insertion and dense code-switching (for a detailed explanation, see Figure 1). Using this typology, Treffers-Daller hypothesized an *Inhibitory control continuum* (Treffers-Daller, 2009), which posits that higher degrees of separation of languages require high levels of inhibitory control (Figure 1). In this view, alternation would be the most demanding type of code-switching in terms of inhibitory control. Insertion requires medium levels of inhibitory control, as one of the languages needs to be inhibited only for single lexical items. Finally, dense code-switching recruits inhibitory control processes the least, due to the minimal levels of language separation. On the flip side, the high degree of cooperation between the two languages on the grammatical and lexical level in a dense code-switch is assumed to pose high demands on monitoring skills (Hofweber et al., 2016).

[Insert Figure 1]

Hofweber and colleagues (2020b) tested the hypothesis that different code-switching types require different levels of proactive and reactive inhibitory control. *Reactive inhibitory control* refers to inhibition as an immediate, unplanned reaction to a cue. *Proactive control* is the ability to prevent an unwanted reaction by sustained active maintenance of the goal-relevant information even before a cue has occurred (Braver, 2012; Gavazzi et al., 2020). In alternation, speakers stick to one of the languages for a prolonged period. Thus, switching occurs relatively infrequently, suggesting that the strategy in speakers who use alternation often is an immediate

reaction to the relatively rare switch. In contrast, unrelenting transitioning between the two languages in dense code-switching is assumed to require proactive control to stay prepared for inhibition or facilitation of short linguistic stretches from both languages (Hofweber et al., 2020b). They developed an ecologically valid code-switching frequency task (CSFT) to capture the habitual code-switching patterns using authentic instances of German-English code-switches from corpora. The scores from CSFT were subsequently correlated with reaction times on two types of the flanker task, each of which tapped either into proactive or reactive control based on the proportion of conflict and non-conflict trials (Kałamała et al., 2018). The results revealed that bilinguals' engagement in dense code-switching explained performance in proactive monitoring conditions, whereas engagement in alternation was linked to inhibitory advantage typical for reactive inhibitory control. Ultimately, the findings regarding alternation support the *Inhibitory control continuum* (Treffers-Daller, 2009). Moreover, the findings concerning dense code-switching go beyond this model's hypotheses in revealing that this type of code-switching requires proactive monitoring.

Taken together, the level and type of the cognitive control processes required for code-switching differ based on directionality and the relative separation of both languages. This raises the question which neural substrates enable this differential engagement of cognitive control processes employed during code-switching.

1.3 Neurophysiological substrate of code-switching

According to neurocognitive models of bilingual language control and processing, the cognitive control processes enabling language switching and inhibition of one of the languages are assumed to be domain-general (Abutalebi et al., 2008; Casaponsa et al., 2015; Green & Abutalebi, 2013; Liu et al., 2020). Important regions associated with both cognitive control and switching include the anterior cingulate cortex (ACC) and pre-supplementary motor area (pre-SMA) which are involved in error detection and conflict monitoring (Abutalebi et al., 2012). Further, the dorsolateral prefrontal cortex (DLPFC) and supramarginal gyrus (SMG) are linked to attention, conflict resolution and control for possible interference (Jost et al., 2020). Critically, all the above-mentioned cognitive processes are mediated and supported by subcortical regions, specifically the caudate nucleus, putamen, globus pallidus and thalamus (Beste et al., 2018). It is assumed that these structures function as a gate employing the appropriate set of cognitive control processes needed to enable bilingual use and also attain goals in general (Green, 2018). The remainder of this introduction will focus on these structures in more detail, because of their prominence in regulating cognitive processes during switching.

Among the subcortical regions, the caudate nucleus is arguably the single most crucial structure subserving code-switching (Green, 2018; Ramezani et al., 2020). It has been reported to be active during language switching in general, during the processing of intrasentential code-switches (Rossi et al., 2021), and its activation has been shown to be modulated by language switching training (Kang et al., 2017). In addition, its activation has been linked to inhibitory control and resolution of verbal interference (Ali et al., 2010). As for the putamen, globus pallidus and thalamus, their role in code-switching has been less studied, but they have been suggested to function as detectors of the salient cues resulting in faster inhibition responses (Green & Abutalebi, 2013). Thalamic activation has been reported in studies on proactive inhibition, indicating that the thalamus is involved in maintaining a state of high alert or vigilance and in keeping inhibitory control processes on stand-by mode for prolonged periods of time (Eckert et al., 2009; Gavazzi et al., 2020). The thalamus is regulated by the globus pallidus and putamen during these processes, which suggests a joint orchestration of cognitive control processes by these three regions (Aron, 2011; Gavazzi et al., 2019).

Clinical research provides important support for the significance of the caudate nucleus and the thalamus in language selection and inhibition of languages in code-switching. This evidence comes from studies on individuals suffering from pathological language switching, the uncontrollable mixing of both languages even within a single utterance. Notably, the afflicted individuals have no cognitive or intellectual decline. Thus, this condition has been ascribed to a deficit in the employment of the appropriate cognitive control processes to control the mixing of two languages (Goral et al., 2019), and has been associated with atypical morphology of the caudate nucleus (Abutalebi et al., 2000) and vascular damage of the thalamus (Mariën et al., 2005).

The thalamus and the caudate nucleus constitute part of the cortico-basal ganglia-thalamo-cortical loop (de Kloet et al., 2021). This circuit is involved in evaluating context and selecting the appropriate cognitive control processes through the basal ganglia (e.g., the caudate nucleus), with the thalamus being involved in overruling strongly activated or automatic goal-directed actions (Wei & Wang, 2016). In the context of language switching, the caudate nucleus is likely responsible for selecting the appropriate language(s) as a function of predicted outcomes, allowing for activation of lexico-semantic systems relevant for a given moment (Hervais-Adelman et al., 2015b). Conversely, the thalamus is assumed to be involved in high-end cognitive control requiring strong inhibitory or facilitatory responses (de Kloet et al.,

2021), an example of which is suppression or reactivation of the dominant language (Yuan et al., 2021).

1.4 Bilingualism-induced structural brain changes in the thalamus and the caudate nucleus

Both the caudate nucleus and the thalamus have been reported to adapt structurally due to bilingualism (Burgaleta et al., 2016; DeLuca et al., 2019; Hervais-Adelman et al., 2018; Pliatsikas et al., 2017). For example, DeLuca and colleagues (2019) used the Language Social Background Questionnaire (LSBQ, Anderson et al., 2018c) to quantify bilingual experiences, including code-switching, in different settings (at home and in social/community settings). They investigated how bilingual experiences as measured by the continuous LSBQ scores affect the volumes of key brain regions in bilinguals that were highly immersed in an L2-speaking environment. DeLuca and colleagues (2019) revealed that expansion of the left caudate nucleus and the right thalamus positively correlated to the use of both languages in the community setting but not to their use in the home setting. These findings indicate that the context within which participants use their languages could place different demands on language control processes (Anderson et al., 2018c), which may also relate to different code-switching needs (Green & Abutalebi, 2013). According to ACH, in the home setting, bilinguals with a migratory background, like those in the DeLuca et al. study, are expected to often engage in intrasentential types of code-switching. In contrast, in the community setting, bilinguals predominantly switch between sentences or switch their languages when conversing with different interlocutors (Green & Abutalebi, 2013). However, such a view is not supported by other studies which show a broad variability in habitual code-switching patterns across bilingual communities (Backus, 2005; Lai & O'Brien, 2020).

Korenar et al. (2021) followed up on DeLuca et al. (2019) but they additionally tested their hypotheses that the effects of bilingualism on the brain may be nonlinear (Pliatsikas, 2020) by using Generalised Additive Models (GAMs) for modelling possible non-linear brain adaptations (Pliatsikas, 2021; Pliatsikas et al., 2020). The study showed that volumes of the thalamus related linearly, and volumes of the caudate nucleus related non-linearly to the degree of bilingual experiences as measured using a composite score derived from the LSBQ, which subsumes information about code-switching frequency. Thus, the reported volumetric adaptations could be partly ascribed to code-switching practices. Notably, volumes of caudate nuclei increased from the low-end to the mid-range of bilingual experience scores but decreased towards the high-end. These findings are consistent with the suggestion that the

effects of bilingual practices on brain structure can be complex and non-linear, as predicted by the Dynamic Restructuring Model (DRM, Pliatsikas, 2020). However, whether specific aspects of bilingual experiences such as code-switching practices also trigger non-linear changes, and under what circumstances they may do so, remains unclear.

Collectively, the results of DeLuca et al. and Korenar et al. suggest that structural adaptations of the regions critical for language switching can be predicted by continuous measures of bilingual language use containing information about code-switching practices alongside other types of bilingual experiences. However, since these measures have not successfully differentiated between these experiences, it is impossible to determine which of them contributed to the observed structural effects and to what extent. Although information about language context can serve as a proxy for language switching practices, only a direct assessment of actual code-switching practices can provide a clearer picture of the relative contribution of this bilingual behaviour to structural brain adaptations. Therefore, to make a step-change in our understanding of structural brain correlates brought about by code-switching, it is critical to use an specific, direct, fine-grained measure of code-switching practices. Also, to reveal any possible non-linear patterns, it is necessary to use non-linear statistical tests.

1.5 The current study

The current study aims to meet the challenges outlined above by examining structural brain adaptations brought about by code-switching practices in Czech-English advanced bilinguals. Here we focus on the caudate nucleus and the thalamus, which have been consistently reported as essential nodes for code-switching (Green & Abutalebi, 2016; Ramezani et al., 2020). Our approach is innovative because of the in-depth focus on different types of code-switching practices, which was made possible by the creation of a Czech-English version of the Code-switching frequency task (CSFT) (Hofweber et al., 2016). This task provides information not only about participants' overall code-switching frequency, but also about their usage frequency of four code-switching types. We distinguish between three types of intrasentential code-switching (alternation, insertion and dense code-switching) as well as intersentential code-switching (switching between sentences). We examine whether the degree of engagement in various code-switching types bears distinct relations to brain structure. In addition to code-switching type, we will also investigate whether directionality of code-switching plays a role in structural brain adaptations (Bobb & Wodniecka, 2013), and whether the effects of usage

frequency of different code-switching types differ with respect to the directionality of the switch.

Since the caudate nucleus has been consistently implicated in inhibitory control and monitoring during code-switching, we expect its volume to correlate positively with the use of all code-switching types. Furthermore, since alternation and intersentential code-switching have been shown to require high levels of inhibitory control processes due to the high degree of language separation (Hofweber et al., 2016, 2020b; Treffers-Daller, 2009), higher engagement in these code-switching types is expected to positively correlate to volumes of the thalamus, an essential structure for inhibitory control (Gavazzi et al., 2020). As directionality of code-switching modulates cognitive control demands (Bobb & Wodniecka, 2013), we predict that high engagement in L2-L1 code-switches will result in more pronounced structural effects compared to switches in the opposite direction.

2 Methods

2.1 Participants

45 (22 females, 23 males) Czech-English bilinguals participated in the current study [mean Age (SD): 28.75(7.62)]. All participants gave informed consent and the experimental procedure was approved by the Ethics Committee of the Masaryk University (Ref. No. EKV-2020-013). All participants were neurologically healthy, right-handed, without MRI contradiction and normal or corrected-to-normal vision. Participants indicated that they use English regularly and have intermediate to advance English proficiency. Their English proficiency was assessed using LexTale (Lemhöfer & Broersma, 2012), a test scoring vocabulary knowledge on a 0-100 scale [mean LexTale score (SD): 76.93(12.28)]. All participants lived in the Czech Republic at the time of testing and indicated that they had not travelled abroad during the two weeks before the testing. Only native speakers of Czech were included in the current study. In Czechia, education and parental education are very strong determinants of the socioeconomic status (Greger, 2012). In this respect, all participants had a uniform socioeconomic status as all of them held a university degree or were enrolled in a university programme, and at least one of their parents held a university degree (i.e., bachelors, masters, PhD or MD).

2.2 Materials

Code-switching frequency task

To assess the frequency of Czech-English code-switching types that participants engage in. Frequency judgements have been argued to be a valid indicator of participants' code-switching productive habits (Backus, 2015; Hofweber et al., 2019). The stimuli consisted of 80 Czech-English code-switches containing eight sentences of each code-switching type using the criteria described by Muysken (2013): 1) alternation from English to Czech, 2) alternation from Czech to English, 3) insertion of English into Czech, 4) insertion of Czech into English, 5) dense code-switching of Czech into English, 6) dense code-switching of English into Czech, 7) intersentential code-switching from Czech to English, 8) intersentential code-switching from English to Czech. The stimuli were predominantly authentic utterances collected from social media conversations among Czech-native university students at the University of Reading. The length of the stimuli was adjusted so that all sentences consisted of thirteen syllables. The types of code-switching which could not be found in such conversations were derived from authentic instances of Czech-English code-switching reported in other studies (Klimpfinger, 2009; Myslín & Levy, 2015; Podlipský & Šimáčková, 2015), or were translated based on code-switches documented in research on other Slavic languages with English, including Polish (Dąbrowska, 2013), Macedonian (Hlavac, 2016), Serbian (Savić, 1994) and Russian (Chirsheva, 2009; Sichyova, 2005). The code-switching stimuli based on the translation from other languages were assessed for their adequacy by an independent Czech-native trained linguist. The stimuli for this task can be found in *Appendix A*.

Prior to the administration of the frequency judgment task, participants were invited to imagine a casual, informal conversation with a Czech-English bilingual friend. The code-switching sentences were recorded and presented audio-visually in pseudo-randomised order using the experimental software E-prime 3.0 (Psychology Software Tools, Pittsburgh, PA). For the pseudo-randomisation, we created stimuli sets consisting of all code-switching types represented by one sentence within each set. The order of appearance of the sets was fully randomised and so was the order of the stimuli within each set. The participants' task consisted of rating the utterances based on the frequency with which they would encounter them in daily life. Thus, the participants were asked to judge the frequency of the utterances rather than their acceptability (Hofweber et al., 2016). This decision is in line with research showing that usage of code-switching is often stigmatised (Treffers-Daller, 1992), and a question about acceptability could invite participants to attitudinally biased responses. Participants rated their

judgment using a visual analogue scale (Llamas & Watt, 2014). This was a sliding continuous scale allowing for decimal points, with an internal range of 1-7, with visual clues discriminating no other scale points besides the extremes and the middle point. The three highlighted points were accompanied with verbal descriptions in Czech: “Podobné věty slyším neustále” (= I am used to encountering similar sentence all the time) and “Podobné věty nikdy neslyším” (= I never encounter similar sentences) for the extremes and “Podobné věty tu a tam slyším” (= I am used to encountering similar sentences every now and then) for the middle point. Participants familiarised themselves with the task on five training sentences prior the actual experiment. The whole frequency judgment task took up to 30 minutes. The descriptive statistics of the CSFT scores are illustrated in Table 1, which shows the frequency of all code-switching types collapsed into average scores. The descriptive statistics of frequencies of individual code-switching types in different directions can be found in Table 2 and their illustrating plot can be found in *Appendix B*.

[Insert Table 1 and 2]

2.3 Neuroimaging data collection

High-resolution anatomical scans were collected using 3T Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil at the Central European Institute of Technology in Brno, Czechia, with the following parameters: sagittal orientation, 256 slices, 0.7 mm slice thickness, voxel size 0.7 x 0.7 x 0.7 mm, acquisition matrix 246 x 256 mm, in-plane resolution 250 x 250, TE = 2.41 ms, TR = 2400 ms, inversion time 1140 ms, flip angle 8°. The T1 structural scans were collected in approximately 10 minutes.

2.4 Data pre-processing

The raw structural T1-weighted images were pre-processed using the FSL_anat software pipeline (Jenkinson et al., 2012). We used the FIRST tool which implements the Bayesian Appearance Model (Patenaude et al., 2011) to automatically segment the volumes of caudate nuclei and thalamus. Quality control of the automated segmentations was performed visually by two trained researchers and adjusted manually, if necessary, before the individual volumes were calculated. To account for variations in the regional volumes of interest among participants stemming from individual differences in overall head sizes, we employed the *proportion method* (O’Brien et al., 2011). Thus, we divided the absolute volumes of regions of interest by the whole-brain volume to obtain the proportional volumes of the caudate nucleus

[mean proportional volumes multiplied by 1000 (SD): 2.63 (0.24)] and the thalamus [mean proportional thalamic volumes multiplied by 1000 (SD): 5.75 (0.37)].

2.5 Statistical analysis

Generalised additive mixed models (GAMMs)

We analysed the data with generalised additive mixed models (GAMMs) (Wood, 2017), utilising the function *gam()* from the package *mgcv* (Wood, 2011) in the statistical software R in RStudio Version 1.4.1106 (R Core Team, 2019). GAMMs allow for the modelling of non-linear relationships by implementing penalised smoothing splines. Smoothing splines are non-linear regression lines that can be bent if a non-linear relationship captures the variance in the observed data more effectively. The curved form of the smoothing spline is calculated as a sum of simpler basis functions, which causes the models explained by the non-linear relationship to be also mathematically more complex and potentially overfitted. To prevent overfitting by modelling too many basis functions, we employed the *Restrictive Maximum Likelihood Approach*, in which the introduction of the “wiggleness” comes with a penalty to the overall model fit (Wood, 2011). Consequently, non-linearity is introduced in a model only if the variance explained by a wiggly line outweighs the penalty attached to it (Wood, 2020).

To establish whether the effects of code-switching frequencies on grey matter volumes are different in each hemisphere of the ROIs, we examined the interactions of all *Code-switching frequency types* with *Hemisphere* using the “vibration of effects approach” (Patel et al., 2015). For each ROI, we ran two GAMMs with both levels of ordered factors of *Hemisphere* as reference levels. The effects of the interactions *Hemisphere x Code-switching frequency* did not emerge significant in both relevant versions of the model with different reference levels. Thus, in further analyses, we focused on the main effects of code-switching frequencies in the volumes of caudate nucleus and thalamus averaged across hemispheres.

Separate GAMMs were run for normalised volumes of the thalamus and caudate nucleus (averaged across hemispheres) as predicted variables and for various code-switching frequency scores (see below) as the key independent variables. Moreover, in all GAMMs, we controlled for the age-related structural adaptations by including *Age* as a possible non-linear covariate and *Gender* as a categorical variable to account for sex-related differences in regional volumes sizes. *Subject* was entered into all models as a random effect to account for between subject differences. We considered adding the *LexTale scores* (used here to index English

proficiency) as a predicting variable using *the Double penalty approach* (Marra & Wood, 2011), a data-driven, empirical Bayes procedure to identify variables that do not contribute to the variance of observed response values. The procedure established that *LexTale* scores did not strongly affect the regional brain volumes (all p values > 0.172; see *Appendix D*) and the *LexTale* scores were not added to the models. All GAMMs in this study had the same structure. However, for clarity purposes, we compartmentalised the models into four thematically related sets of analyses based on the key dependent variable.

In the first set of analyses, three GAMMs were run with three overall code-switching frequency scores: i) overall code-switching frequency, which was a grand average of all trials from the CSFT, ii) overall code-switching frequency of code-switches from L1 to L2, which was a grand average of frequencies of all code-switching types in this direction, iii) overall code-switching frequency of code-switches from L2 to L1, which was a grand average of frequencies of all code-switching types in the direction English-Czech.

In the second set of analyses, we investigated the effects of the code-switching frequency of each code-switching type without considering their directionality. Thus, we ran four separate models with the following key predictors: i) Frequency of intersentential code-switching, ii) alternation, iii) insertion, and iv) dense-code switching.

The third set of analyses focused on the effects of directionality of each code-switching type on volumes of the thalamus and caudate nucleus. Thus, we ran eight models with the following frequency scores entered as key dependent variables: i) Frequency of intersentential code-switching from L1 to L2, ii) intersentential code-switching from L2 to L1 iii) alternation from L1 to L2, iv) alternation from L2 to L1, v) insertion from L1 to L2, vi) insertion from L2 to L1, vii) dense code-switching from L1 to L2, viii) dense code-switching from L2 to L1.

3. Results

The results from the four sets of GAMM analyses are presented here for the key predictor variables. Reports of other predictors from all models discussed here can be found in the *Appendix C*.

3.1 Overall code-switching frequency

As shown in shown in Figure 2, the overall code-switching frequency emerged as a highly significant positive predictor of the volumes of caudate nuclei, but not of the thalamus.

3.2 Overall code-switching frequency – split by directionality

Results from this analysis are illustrated in Figure 2. Code-switching frequency in both directions emerged as a significant positive predictor of the volumes of the caudate nucleus, with the effect for the L2 to L1 direction emerging as non-linear. No significant effects emerged for either code-switching direction on the volumes of the thalamus.

[Insert Figure 2]

3.3 Frequency of individual code-switching types and their effects on the caudate nucleus and thalamus

Results from this analysis are illustrated in Figure 3. Specifically, the volume of caudate nucleus were positively significantly related to the usage frequency of intersentential code-switching, alternation, and insertion, but not of dense code-switching. Regarding the volume of the thalamus, frequency of only intersentential code-switching and alternation emerged as significant predictors, whereas dense-code switching emerged as a marginally significant predictor.

[Insert Figure 3]

3.4 Frequency of individual code-switching types and their effects on the caudate nucleus and thalamus – split by directionality

Results from these analyses are shown in Figure 4. With respect to the L1 to L2 direction, engagements in all code-switching types were revealed as significant predictors of volumes of the caudate nucleus. Intersentential code-switching frequency emerged as the only significant non-linear predictor of volumes of the thalamus, manifesting a U-shaped relationship with the right maximum larger than the left maximum. With respect to the L2 to L1 direction, only frequency of intersentential code-switching and alternation were highly significantly related to the volumes of the caudate nucleus, whereas dense code-switching frequency was only a marginal predictor. Moreover, alternation and intersentential code-switching frequencies emerged also as significant non-linear predictors of thalamic volumes. All reported effects were overall positive in that higher engagement in these code-switches was linked to larger volumes in the relevant regions. Notably, intersentential code-switching was a significant predictor and triggered a U-shaped volumetric trajectory of thalamic volumes with the right-sided maximum larger than the left maximum, suggesting an overall positive relation

[Insert Figure 4]

4. Discussion

In this study, we aimed to identify patterns of structural brain adaptations linked to engagement in code-switching, a uniquely bilingual and cognitively demanding linguistic act. Specifically, we examined the effects of overall code-switching frequency on the caudate nucleus and the thalamus, two crucial regions for code-switching, and whether the directionality of the switch and engagement in various types of code-switching have distinct effects. It has been argued in the Dynamic Restructuring model (DRM) that bilingualism-related changes in brain structure occur in regions that subserve the given bilingual task (Pliatsikas, 2020). The DRM posits that the changes in the relevant structures will be related to the intensity and quality of the concrete experiences. Expanding on the DRM, we here opted for a nuanced, quantified, and continuous assessment of code-switching habitual practices with the aim to reveal how the dynamicity of concrete bilingual experiences can contribute to structural brain changes.

We showed that the overall frequency with which participants engage in code-switching relates positively to volumes of the caudate nucleus. Furthermore, frequent use of code-switching types in which the two languages are more separated consistently predicted larger volumes in both the caudate nucleus and the thalamus. In so doing, this study is the first to suggest that code-switching is an important modulatory factor of subcortical structural adaptations in bilinguals. The observed effects of engagement in particular code-switching types on brain structure have important implications for studies on the processing of code-switching and bilingualism-induced neuroplasticity, which will be discussed below.

4.1 Effects of overall code-switching frequencies

Overall, our findings support previous empirical studies and theoretical models that put forward the caudate nucleus as one of the prominent subcortical structures in language switching in general (Green, 2018; Luk et al., 2012; Ramezani et al., 2020). In line with our predictions, we reported larger volumes of caudate nuclei to be positively associated with the overall frequency of code-switching and the frequency of code-switching irrespective of directionality (i.e., L2-L1 and L1-L2).). Previous research showed that activation of this structure increased when processing or producing an actual switch (Abutalebi & Green, 2007; Green & Abutalebi, 2013; Rossi et al., 2021). Evidence from clinical research reported that damage to this structure can lead to uncontrollable yet structurally well-formed code-switching (Abutalebi et al., 2000). Also, fMRI studies on switching processing suggested that the caudate nucleus is responsible for the selection of the language systems which will be activated and potentially mixed within

a code-switching utterance (Branzi et al., 2016; Hervais-Adelman et al., 2015). The selection of languages relevant for concrete conversations is, at least to a certain extent, necessary for any language switching. Therefore, by virtue of this functionality, the caudate nucleus should also be involved in all types of code-switching. The positive relationships between volumes of the caudate nucleus with the overall code-switching frequency, and frequency of code-switching in both directions observed here, support this view.

CS frequency did not correlate with thalamic volumes in the same way it did for the caudate nucleus. The thalamus detects cues signalling language switching and subsequently regulates regions responsible for selective inhibition on a moment-to-moment basis (Green & Abutalebi, 2013). As proposed in the *Inhibitory control continuum* (Treffers-Daller, 2009), these cognitive processes are not central to all code-switching types. Therefore, it is possible that the thalamus did not show observable structural adaptations as a function of the overall code-switching frequencies because its role in code-switching might be more specialised than that of the caudate nucleus.

4.2 Effects of frequencies of specific code-switching types

Another goal of our study was to determine whether engagement in different code-switching types (Muysken, 2013) leaves distinct structural signatures on the volumes of the caudate nucleus and thalamus. We based our predictions on the Inhibitory control continuum model and existing empirical studies, which reported that the degree of separation of both languages within a code-switch modulates the cognitive control processes involved (Hofweber et al., 2016, 2020a; Treffers-Daller, 2009). Indeed, our results suggest that differences in volumes in the regions of interest are linked to the degree of separation of both languages.

First, we turn to the results pertaining to the adaptations of the caudate nuclei. Volumes of the caudate nucleus were higher in cases of a higher degree of engagement in intersentential code-switching, alternation and insertion, but not decisively so in dense code-switching, where similar effects emerged as marginally significant. This pattern suggests that, while caudal adaptations are sensitive to all types of code-switching, these adaptations are more pronounced in more separated code-switching types. Code-switches for which both languages are highly separated seem to draw upon reactive inhibitory control processes requiring moment-to-moment inhibition (Green, 2018; Hofweber et al., 2020a). By contrast, the caudate nucleus has been suggested to subserve the selection of the language systems relevant for the current conversation, which does not necessarily require high levels of reactive inhibitory control

(Green, 2018; Hervais-Adelman et al., 2015). However, the current findings suggest that the caudate nucleus is involved in both the monitoring and the selection of language systems and reactive inhibition. This view aligns with that of Branzi and colleagues (2016) who reported increased activation of this structure during control for both single lexical items (i.e., local control) and entire language systems (i.e., global control).

There is existing indirect evidence suggesting that structural adaptations of the caudate nucleus might indeed be sensitive to the modulations of cognitive control processes stemming from the degree of language separation. The expansion of caudate nucleus has been linked to active bilingual language use in community/social settings but not in the home setting (DeLuca et al., 2019). The Adaptive Control Hypothesis suggests that the community setting is characterised by the use of separated forms of switching, such as switching between two sentences (Abutalebi & Green, 2016; Green & Abutalebi, 2013). However, claims that separated forms of code-switching are related to changes of the caudate nucleus could be based only on the proxy that such code-switching forms are typically used more often in a specific interactional context. Although participants in the current study come from comparable interactional context, the results show that they engage to various degrees in all code-switching types under study. Moreover, using a direct measure of the frequency types, the current findings reveal that the degree of separation of both languages in a code-switch has a graded effect on the extent to which the caudate nucleus adapts. Specifically, more pronounced volumetric effects in the caudate nucleus are linked to the separated forms of code-switching.

We found that thalamic volumes increased with more frequent engagement in intersentential code-switching and alternation, which largely corroborates the patterns observed in the caudate nucleus. Thus, and in line with our predictions, thalamic adaptations were significantly related only to the most separated forms of code-switching. This structure is involved in the high-end inhibitory control, regulating and facilitating the activity of ACC, which is responsible for the resolution of language interference and suppression of unwanted stimuli (de Kloet et al., 2021; Ramezani et al., 2020). The current finding that intersentential code-switching leads to thalamic increases also overlaps with findings of thalamic expansions in bilinguals using two languages in the social setting (DeLuca et al., 2019), in which switching is expected to occur only between sentences (Green & Abutalebi, 2013). However, alternation is a code-switch occurring within one sentence. The significant positive effect of alternation frequencies on the thalamus challenges the assumptions in the ACH. Thus, not only switching between sentences, but also highly separated forms of intrasentential code-switching can be

linked to structural adaptations in the thalamus. Alternation has also been previously linked to reactive inhibitory control processes (Hofweber et al., 2020), but it has remained unclear whether the inhibitory control demands are so high that they should have structural consequences in the brain. Our findings suggest that alternation indeed poses inhibitory control demands that would require structural adaptations in the thalamus, the subcortical hub of inhibitory control, to subserve these processes effectively. However, the current study does not use direct cognitive measures, which would be needed to establish a direct link between thalamic volumes and cognitive control demands.

Overall, the current results are in line with the Inhibitory control continuum model (Treffers-Daller, 2009), which proposed that highly separated code-switching types come with higher inhibitory control demands which in turn lead to structural effects in brain regions supporting cognitive control processes. Moreover, the current findings expand the scope of the Inhibitory control continuum model to include intersentential code-switching on the high-end of the Inhibitory control continuum. Further functional imaging and behavioural research could further strengthen this notion.

4.3 Combined effects of the code-switching type and the directionality

This study also aimed to elaborate on the analysis discussed above by establishing the effects of the directionality of code-switching on the observed structural effects induced by the various degrees of separation between the two languages. In general, switching from the L2 to L1 has been considered more cognitively demanding as indexed by relevant behavioural and electrophysiological results (Bobb & Wodniecka, 2013; van Hell & Wittenman, 2009). In line with this, our hypothesis was that the more demanding code-switching direction would also lead to more pronounced structural adaptations. Our findings suggest that this hypothesis holds for volumes of the thalamus, whereas for volumes of the caudate nucleus, the effect of directionality appears to be more complex.

Volumes of the caudate nucleus appear to be susceptible to change related to the degree of engagement in all types of code-switching but only in the direction from L1 to L2. The assumedly more cognitively demanding directionality, i.e., from L2 to L1, was observed to relate to volumetric effects in the caudate nucleus only for the most separated types of code-switching: intersentential code-switching and alternation. This pattern supports the notion that the caudate nucleus is more involved in switching from L1 to L2, as suggested by previous

studies which showed increased activation of the caudate nucleus only in this direction (Garbin et al., 2011; Hosoda et al., 2012).

In line with our predictions, directionality differentially affects thalamic volumes for alternation. Specifically, higher alternation frequency in switching from L2 to L1, but not from L1 to L2, was linked to increased volumes of the thalamus. On the other hand, intersentential code-switching in both directions was positively related to thalamic volumes, suggesting that this type of code-switching requires on its own high levels of reactive inhibition that are not affected by directionality.

4.4 Conclusion

To the best of our knowledge, this is the first time that code-switching was investigated as a modulating factor of bilingualism-induced structural brain adaptations. This study reveals that engagement in code-switching modulates the neural structure of the caudate nucleus, which is a prominent region subserving language switching. Furthermore, we report that various code-switching types differentiated based on the level of separation of both languages in the code-switch and their directionality, leave distinct structural fingerprints in the volumes of the caudate nucleus and thalamus.

The methodological contribution of this study is two-fold. First, we linked quantified measures of engagement in specific, linguistically distinguishable types of bilingual behaviour with structural brain adaptations. In doing so, we could directly relate this behaviour with the observed structural differences, rather than relying on executive functioning tasks and assuming that these tasks reflect the actual cognitive demands linked to everyday bilingual language use. Second, our models could reveal non-linear volumetric trajectories, placing the current study among those embracing the general principles of experience-dependent neuroplasticity. These results support the notion of the DRM that structural adaptations brought about by bilingual experiences are dynamic and expand on this model by showing that subtly different habitual code-switching patterns may differentially alter volumetric trajectories in subcortical structures.

These findings have important implications for theories on cognitive demands linked to engagement in code-switching such as the Adaptive Control Hypothesis and Inhibitory continuum model. Specifically, the present results suggest that code-switching within two sentences are linked to structural adaptations of regions responsible for reactive inhibitory control, despite the theoretical notion of the ACH that intrasentential code-switching does not

rely on these processes (Green & Abutalebi, 2013). In the same vein, our findings suggest that switching between and within one sentence should not be treated as distinct instances of code-switching in terms of cognitive control processes, but rather as code-switching types that are positioned at different points on the same inhibitory control continuum. Further empirical studies should investigate whether the Inhibitory control continuum (Treffers-Daller, 2009) could be extended beyond intrasentential code-switching to include intersentential code-switching as the most demanding code-switching type.

Taken together, the current findings suggest that engagement in specific code-switching types may condition the observable estimates of brain volumes across bilingual individuals. These results advance existing models on code-switching processing and control, underline the dynamicity of experience-dependent neuroplasticity related to qualitatively diverse code-switching types and the assumed cognitive control demands they bring, and strengthen the notion that the various constituent elements of the bilingual experience may each impact the brain in their own ways. In all, we argue that fine-grained assessment of code-switching practices might be a key to reconciliation of the seemingly contradictory findings in studies on bilingualism-induced brain adaptations.

Author Contributions

The study was conceived and designed by MK, CP and JTD. Data collection was performed by MK. Data preparation and analysis were performed by MK and CP. The manuscript was written by MK and edited by CP and JTD. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing financial interests or commercial considerations and that this material has not been published (nor is it under consideration for publication) elsewhere.

Data Availability Statement

Data used in this study are available from the corresponding author upon reasonable request.

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Tables

Table 1. Descriptive statistics of overall code-switching frequencies obtained from CSFT.

Overall CS frequencies (on the scale 1-7) together indicating the average of frequencies of all code-switching types. Direction of the switch is indicated in the second column.

Average of CS frequencies	Direction	Minimum	Maximum	Mean	SD
Overall CS	Both	1.39	5.19	3.21	0.8
Overall CS	L2 -> L1	1.35	4.82	3.25	0.82
Overall CS	L1 -> L2	1.44	5.56	3.17	0.83

Table 2. Descriptive statistics of frequencies of individual code-switching types

CS frequencies of the individual code-switching types (on the scale 1-7). Direction of the switch is indicated in the second column.

Direction	CS type	Minimum	Maximum	Mean	SD
Both	Intersentential CS	1.73	5.94	3.64	1.06
	Alternation	1.4	5.24	3.65	0.94
	Insertion	1.42	5.58	3.54	0.86
	Dense CS	1.02	4.53	2	0.76
L1 -> L2	Intersentential	1.95	6.01	3.84	1.08
	Alternation	1.75	5.82	4.07	1.04
	Insertion	1	5.34	2.55	0.94
	Dense CS	1.02	5.13	2.21	0.84
L2 -> L1	Intersentential	1.26	5.87	3.44	1.12
	Alternation	1.05	5.29	3.24	1.08
	Insertion	1.83	6.58	4.53	1.09
	Dense CS	1	3.94	1.8	0.76

Figure legends

Figure 1. Inhibitory control continuum proposed by Treffers-Daller (2009) (1A) and examples of authentic Czech-English code-switching (1B-1D).

English words are in black and Czech words in the respective colour. **1B.** In *alternation*, the language stretches appear to be structurally relatively independent on each other. **1C.** The *insertion* example documents lexical items from one of the two languages (na prohlídku; dispute) being inserted into the grammatical structure of the other language. **1D.** In the *dense code-switching*, both content and function words are taken from both languages.

Figure 2. Overall code-switching frequencies and their effects on volumes of caudate nuclei and thalamus.

Effects of overall CS frequencies irrespective of directionality (left column), in the direction L1->L2 (middle column), and in the direction L2->L1 (right column) on the caudate nucleus (A.) and thalamus (B.) volumes. The 95% confidence intervals are depicted in light blue. The significance of the effects is marked in red (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Edf = estimated degrees of freedom (edf = 1: linear slope; edf > 1: non-linear slope). For all significant effects $F_s > 7.5$. Deviance explained by all significant models > 82 %.

Figure 3. Usage frequencies of individual CS types and their effects on volumes of caudate nuclei and thalamus.

Usage frequency (CSFT score on a scale of 1-7, x-axes) of four code-switching types (rows) and their effects on normalised volumes (y-axes) of caudate nucleus and thalamus (columns). The 95% confidence intervals are depicted in light blue. The significance of the effects is marked in red (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Edf = estimated degrees of freedom (edf = 1: linear slope; edf > 1: non-linear slope). For all significant effects in the caudate nucleus $F_s > 4.8$ and in the thalamus $F_s > 3.6$. Deviance explained by all significant models > 81.9 %.

Figure 4. Usage frequencies of individual CS types split by directionality and their effects on volumes of caudate nuclei and thalamus.

Effects of usage frequency of code-switching types (CSFT scores on a scale of 1-7, x-axes) split by the directionality of the switch (large columns) on the normalised volumes (y-axes) of the caudate nucleus and thalamus (column). The 95% confidence intervals are depicted in light blue. The significance of the effects is marked in red (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$). Edf = estimated degrees of freedom (edf = 1: linear slope; edf > 1: non-linear slope). For all significant effects in the caudate nucleus $F_s > 4.6$ and in the thalamus $F_s > 3.6$. Deviance explained by all significant models > 80.1 %.

Figures

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