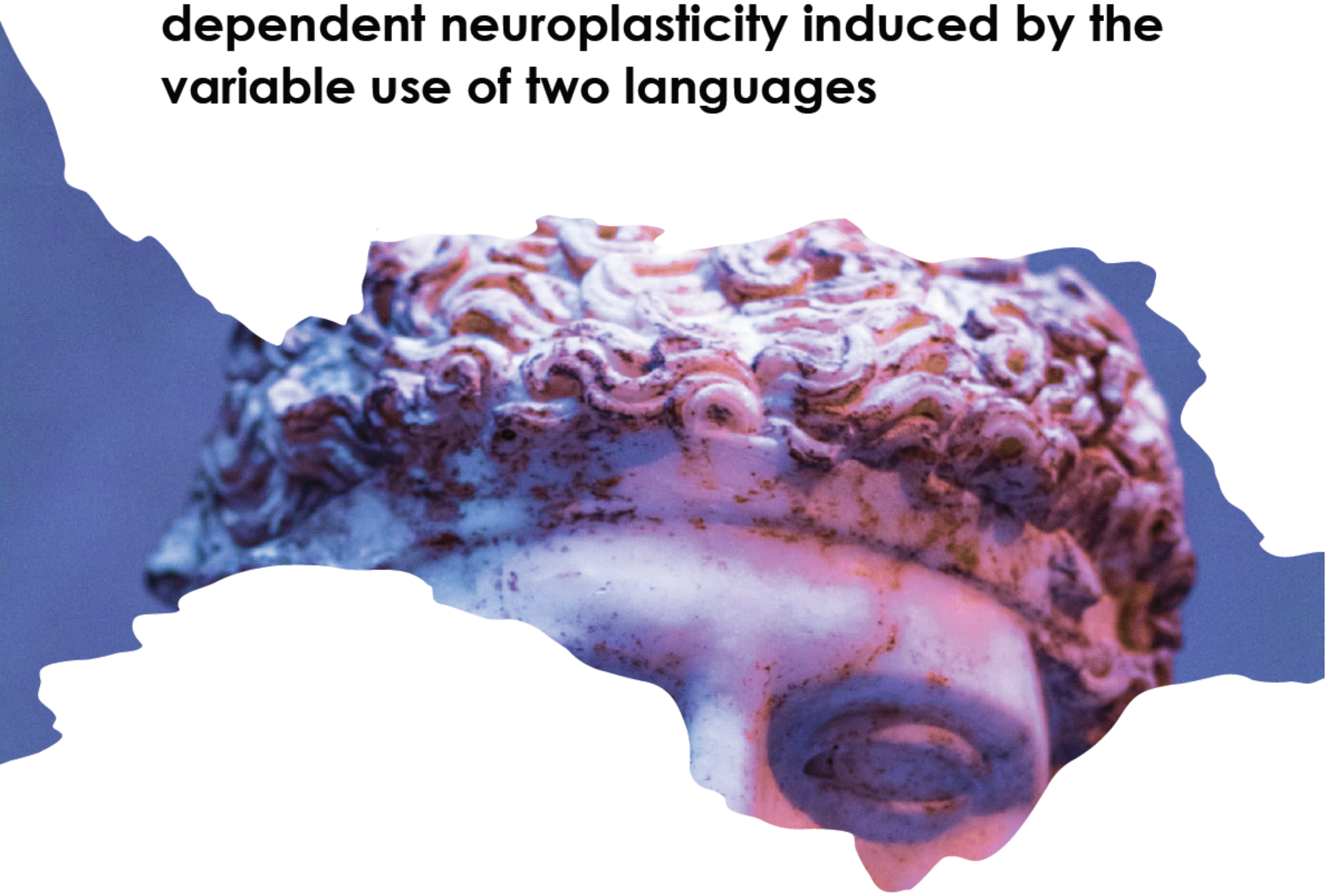
University of Reading

Bilingualism sculpts the core of the brain: an investigation of experience-dependent neuroplasticity induced by the variable use of two languages



Doctor of Philosophy

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"You think that just because it's already happened, the past is finished and unchangeable? Oh no, the past is cloaked in multicolored taffeta and every time we look at it we see a different hue."

— Milan Kundera, Life is Elsewhere

pro mého strýčka Pavla and for Pieter Muysken
for my uncle Pavel a pro Pietera Muyskena

kterým bych býval rád to show this thesis
whom I would have loved tuto práci dal přečíst

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What a journey this has been! Three tiring but very joyful years packed with learning, exploration, laughter, new friendships, and semi-successful struggles with imposter syndrome. This thesis is about how demanding experiences sculpt our brains. My PhD experience has proven to me how powerful a strenuous experience can be in making us unique individuals. I would like to thank all the people who contributed to this sculpting process and made it so very enjoyable. Without you, this thesis would not have been possible, and I would not have been who I am now.

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DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Michal Kořenář

CONTRIBUTIONS BY CHAPTER

Chapter 2

Kořenář, M., Treffers-Daller, J & Pliatsikas, C. (to be submitted). Bilingual experiences induce dynamic structural changes to basal ganglia and the thalamus.

Contributor	Statement of contribution
Michal Kořenář	Study design: 80% Data collection: 100% Data analysis: 90% Writing: 100%
Christos Pliatsikas	Study design: 15% Data analysis: 10% Editing: 70%
Jeanine Treffers-Daller	Study design: 5% Editing: 30 %

Overall contribution of the candidate: 85%

Chapter 3

Kořenář, M., Treffers-Daller, J & Pliatsikas, C. (to be submitted). Sustained bilingual experiences cause nonlinear structural brain adaptations: Insights from interpreters and translators.

Contributor	Statement of contribution
Michal Kořenář	Study design: 80% Data collection: 100% Data analysis: 100% Writing: 100%
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Jeanine Treffers-Daller	Study design: 5% Editing: 30 %

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Chapter 3

Kořenář, M., Treffers-Daller, J & Pliatsikas, C. (to be submitted). Bilingual switching practices have distinct effects on the volumes of the caudate nucleus and the thalamus.

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Michal Kořenář	Study design: 80% Data collection: 100% Data analysis: 90% Writing: 100%
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ABSTRACT

Bilinguals need effective cognitive control mechanisms to handle the concurrent activation of two languages. One of the consequences is that bilingualism has been shown to structurally impact regions subserving cognitive control and language processing to provide a newly wired neural architecture that can handle these mechanisms efficiently. However, the location, extent, and time course of these adaptations vary across studies. The inconsistency has often been attributed to differences in language use and exposure. This thesis extends these proposals and tests a hypothesis, informed by neurobiological principles of experience-dependent neuroplasticity, that the bilingualism-induced brain adaptations are non-linear. Using appropriate statistical methods, three studies are run to investigate the effects of quantified bilingual experiences on grey matter volumes of subcortical regions known to be affected by bilingualism. Structural MRI and behavioural data from 115 bilinguals with a wide variety of bilingual experiences were collected. The first study examines adaptations induced by bilingual experiences in the basal ganglia and thalamus across the whole sample. The second study separately examines bilingualism-induced changes of the caudate and the putamen in interpreters, translators, and non-professional bilinguals. The results from these studies reveal that engagement in bilingual language use can trigger region-specific grey matter increases, either sustained or followed by volumetric decreases, depending on the quantity and quality of bilingual experiences. The third study examines brain adaptations induced by different habitual code-switching practices, which impose different cognitive demands. The results suggest qualitatively diverse volumetric trajectories in caudate and thalamus for the different code-switching types. Overall, this thesis highlights that the various constituent elements of bilingual experiences may impact the brain in dynamic yet systematic ways. Crucially, the systematicity of the experience-dependent neuroplasticity can be unravelled if bilingualism is treated as a dynamic set of demanding experiences which trigger non-linear structural adaptations.

GENERAL INTRODUCTION

More than half of humankind uses more than one language in their daily lives. In addition to the obvious practical convenience of knowing multiple languages, multilinguals seem to benefit economically from their linguistic skills as well. Bilinguals have higher wages than their monolingual counterparts (Christofides & Swidinsky, 2010). On a broader scale, 10% of the national economy of Switzerland, a highly multilingual nation with four official languages, can be attributed to its multilingual heritage (Grin, 2008). In contrast, it has been estimated that Britain annually loses approximately 3.5% of its gross domestic product due to the relatively poor variety in linguistic skills of the British population (Foreman-Peck & Wang, 2014).

While practical convenience and economic benefits already provide justification for continued understanding and promotion of this social phenomenon, bilingualism has been stealing headlines in recent years because of yet other reasons. Namely, speaking two or more languages appears to positively affect humans' minds and brains (Quinteros Baumgart & Billick, 2018), which has nurtured hopes that multilingualism could ameliorate trajectories of cognitive and neural decline (Voits et al., 2020).

These effects are ascribed to the fact that bilingualism is a cognitively demanding life-long experience that requires managing two languages which are constantly activated in parallel in bilinguals' minds (Marian & Spivey, 2003). That is, bilinguals need to continuously resolve an unrelenting conflict of which of their languages to use, and which to avoid in various conversational environments (Kroll et al., 2012). The managing of two languages is hypothesised to be so demanding that the brain needs to adapt structurally to provide the adequate neural architecture to handle these demands effectively (Kroll et al., 2015).

Although the potential beneficial effects of bilingualism have received great attention in the public debate, the academic discussion on this topic is still ongoing and has not offered complete answers (Leivada et al., 2021). The specific effects of bilingualism on cognition and the brain are still poorly understood, which is reflected in variable results in terms of cognitive (Gunnerud et al., 2020; Valian, 2015; van den Noort et al., 2019) and neural effects (Celik et al., 2020; García-Pentón et al., 2016; Pliatsikas, DeLuca, et al., 2020). These seemingly inconsistent findings have sparked a controversy and have prompted a discussion on how the field should move forward in determining the effects of bilingualism on neurocognition (de Bruin et al., 2021; de Bruin & Della Sala, 2016; Paap et al., 2017), with some even pondering whether this line of research should not be abandoned altogether (Paap et al., 2015).

A brief look at cognitive and neural research helps underline the discrepant findings, which are discussed in detail in the subsequent sections. With respect to cognitive effects of bilingualism, some researchers reported improved behavioural outcomes in bilinguals compared to monolinguals, for example in the suppression of interfering information (Bialystok et al., 2004), mental flexibility (Prior & Macwhinney, 2010), and even creativity (Kharkhurin, 2009). However, such findings have not been consistently replicated (Lange et al., 2020; Paap, 2019). Structural imaging evidence has been more consistent in that it has shown that learning and using several languages is linked to anatomical brain changes in a priori predicted parts of the brain that control language learning and cognitive control (Tao et al., 2021; Pliatsikas & Luk, 2016). However, not all the implicated regions appear to change their structure consistently across studies on different populations, and the effects span both increases and decreases in the magnitude of neural measures (Pliatsikas, 2020; Tao et al., 2021). Moreover, the interpretability of neuroanatomical findings also brings ambiguity. Namely, a decrease in the magnitude of neural measures, such as a decrease in regional brain volumes, can signify both increased efficiency of the concerned neural resource to subserve a given task, or that the given structure is not crucial for the given task overall (Paap et al., 2015).

For both behavioural and neural findings, it has been argued that a substantial part of the inconsistencies across studies stems from the binary operationalisation of the terms *bilingual* and *monolingual* (Luk & Bialystok, 2013). That is, the fact that someone does or does not speak two languages likely does not put them in one of two populations with stable differences in their linguistic experiences (Luk & Bialystok, 2013). Consequently, calls have been made to move away from a binary view of mono- versus bilingualism (DeLuca et al., 2019; Luk & Bialystok, 2013). Currently, the field is advancing towards an appreciation of the diversity of experiences held within the group of bilinguals. Ultimately, this marks a new focus of bilingualism research: Which bilingual experiences and/or their combined effects can trigger reliable modulations of brain and cognition?

Despite the advancements with respect to the investigation of effects of individual bilingual experiences in more detail, many important experiential factors have not received much attention, such as habitual code-switching patterns or effects of interpreting and translating practices.

Although these aspects of bilingual behaviour have been widely hypothesised as substantial modulators of cognitive demands (Blanco-Elorrieta & Pylkkänen, 2017; García et al., 2020), our understanding of their contribution to structural brain changes is still very limited. Moreover, another possible source of divergent results has so far remained widely unexplored: the insufficient incorporation of the neurobiological principles of experience-dependent brain changes into study objectives. Behavioural progression in experience towards efficiency and structural brain changes follow distinct trajectories (Wenger et al., 2017). Moreover, these trajectories are hypothesised to be non-linear and highly dynamic, depended on the timing, quality, and quantity of the experiences which induce them (Lindenberger & Lövdén, 2019).

A recently proposed *Dynamic Restructuring Model* (DRM; Pliatsikas, 2020) embraced the principles of non-linear relationships between experiences and brain alterations, applying them in the context of bilingualism-induced neuroplasticity. Crucially, this model kindled an important line of thought, namely that the patterns of bilingualism-induced structural brain changes may be complex and dynamic but at the same time greatly regular. In all, testing the DRM's predictions of non-linear experience-dependent brain adaptations holds an untapped potential to reconcile the seemingly inconsistent effects of bilingual language use on the brain.

This thesis builds on the suggestions to assess bilingualism as a set of experiences on a continuum and focus on the variability within bilinguals themselves, which marked promising ways forward to investigate the effects of bilingualism on brain structure. Moreover, it aims to extend them to principles of experience-dependent neuroplasticity and the investigation of understudied aspects of bilingual language use, such as code-switching behaviour and practices of professional bilinguals. In addition, this thesis focuses on structural brain changes in previously hypothesised hubs of bilingual language control: the basal ganglia and the thalamus (Green & Abutalebi, 2013). Overall, it sets out to put bilingualism forward as a life-long, complex and transforming experience, and to make a step change in our understanding of sources of variability in bilingualism-induced brain changes.

The next section of this thesis will provide a brief overview of literature on the cognitive effects of bilingualism. Subsequently, the neural substrates implicated to subserve bilingual language control will be discussed, as well as the consequences of bilingual experiences on brain structure with special focus on subcortical regions. Afterwards, the available evidence on bilingualism-induced structural adaptations will be reviewed through the lens of experienced-dependent neuroplasticity. The introduction will conclude with the aims of the current project and an outline of the thesis.

1.1 EFFECTS OF BILINGUALISM ON DOMAIN-GENERAL COGNITIVE PROCESSES

Bilingualism can be defined in many ways. This project submits to probably the most liberal definition that a bilingual is *"[a]ny person who knows at least a few words in a language other than the maternal […]."* (Edwards, 2004: 7). Even a limited knowledge and use of additional languages brings aspects of a complex life-long experience that requires managing several languages in one mind in various social environments. Crucially, one of the critical discoveries within bilingualism is that the acquired languages are both active, even if bilinguals intend to use only one of them (Kroll et al., 2012; Marian & Spivey, 2003). This comes with cognitive challenges. For example, when speaking with monolinguals, bilinguals' brains must make sure to choose the language appropriate for that particular situation while inhibiting the other language. Conversely, when in conversations with other bilinguals with similar language backgrounds, bilinguals often choose to code-switch; that is, they freely alternate between two languages within one paragraph or even one sentence (Appel & Muysken, 2005). Here, bilinguals must constantly monitor the situation and lexical and grammatical units from both languages to make their utterances comprehensible despite the mixing of languages (Blanco-Elorrieta et al., 2018). These are just two examples of bilingual behaviours that require executive functions, which are sets of cognitive processes enabling goal-directed behaviour (Green, 2018; Kroll et al., 2015). The daily handling of two languages is hypothesised to result in a "training" and potential enhancement of executive functions (Bialystok et al., 2012). Crucially, these cognitive processes are assumed to be domain-general, that is, they are used across many activities beyond language use (Costa et al., 2009).

In their influential model, Miyake and colleagues distinguish inhibition, switching, and monitoring and updating as the three types of executive functions (Miyake et al., 2000). Previous studies presented behavioural evidence for the strengthening of inhibitory control in bilinguals compared to monolinguals in a variety of inhibitory control tasks such as the Simon task (Martin-Rhee & Bialystok, 2008), the Stroop task (Bialystok et al., 2008)or the Flanker task (Eben & Declerck, 2019)[1]. These tasks share the presence of congruent trials (trials where target stimuli are accompanied by informational cues which favour the target response) and incongruent trials (trials

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[1] Note that the list of tasks used is far from exhaustive and the selection of tasks was motivated purely for illustration purposes. For further information on executive function and the tasks used see Morra and colleagues (2018).

where the accompanying informational cues conflict with the correct response). For example, in the Flanker task, which measures inhibitory control (Eriksen & Eriksen, 1974), the stimuli are rows of five arrows. One of the arrows (generally the middle one) is the target stimulus, and participants need to indicate the direction of this arrow by pressing a corresponding button. In congruent trials, all the arrows point in the same direction as the target (→→→→→ or ←←←←←). In the incongruent trials, the accompanying (i.e., flanking) arrows point to the opposite direction than the target (→→←→→ or ←←→←←). The expected difference in reaction time before pressing the correct button between congruent and incongruent trials, as well as the difference in accuracy scores in pressing the correct button, is referred to as to the flanker effect, or the conflict effect (Eriksen & Eriksen, 1974). In the context of flanker task and other similar executive control tasks (i.e., Simon or Stroop task), smaller conflict effects are traditionally interpreted to reflect an increased ability to inhibit unwanted information and resolve conflict.

Bilinguals have been found in several studies to have smaller conflict effects than monolinguals, which has been interpreted as evidence that bilinguals outperform monolinguals in cognitive conflict resolution and inhibition (Bialystok et al., 2004; Costa et al., 2008). Several other studies presented evidence which suggests that bilinguals are generally faster in both congruent and incongruent trials than monolinguals (Costa et al., 2008; Martin-Rhee & Bialystok, 2008). As there is no misleading information to be inhibited in the congruent condition, being faster at these trials cannot be linked to enhancement in inhibition (Martin-Rhee & Bialystok, 2008).

Another strand of research further differentiated between executive functions, specifically between monitoring and inhibition, by manipulating the proportionality of congruent and incongruent trials in executive control tasks. In this view, an equiprobable proportion of congruent and incongruent trials (50% and 50%) is assumed to tap into monitoring skills, due to the assumption that the possible advantage in this condition stems from a constant readiness to monitor the situation and to react accordingly. By contrast, in the case of a highly disproportional representation of congruent trials, the rare occurrence of conflict trials prompts participants to relax their monitoring skills and rather to rely on inhibitory control on a moment-to-moment basis (Kałamała et al., 2018). A study using both variations in a flanker task revealed that bilinguals had overall shorter reaction times than monolinguals only on the high monitoring condition (50/50 trial type split), which was interpreted as an indication that bilinguals have a monitoring advantage rather than a conflict resolution advantage (Costa et al., 2009).

The distinction between inhibition and monitoring largely aligns with the proposition of the Dual Mechanisms of Control Framework (DMC), which uses the terms proactive and reactive control (Braver, 2012). A proactive control strategy resembles monitoring and refers to active preparation for a conflict in advance through an active reminder of the goal of the task. Reactive control involves the suppression (inhibition) of a prepotent response in reaction to a stimulus after it is presented (Mäki-Marttunen et al., 2019).

Existing reviews on proactive and reactive control in bilinguals and monolinguals state that bilingualism appears to have more consistent effects on proactive control processes than on reactive ones (Bialystok et al., 2012; Declerck, 2020). A different conclusion was drawn by Hilchey and colleagues (2015) who did not find support for the proactive control advantage in bilinguals. Overall, these findings contribute to the controversy about the overall robustness of results that suggest that bilingualism confers benefits on executive functioning (Lehtonen et al., 2018; Paap, 2019). Namely, the findings highlight that the cognitive differences between bilinguals and monolinguals do not emerge consistently and differ in the type of executive control investigated. Adding to the controversy, a number of studies on the modulation of cognitive processes in bilinguals compared to monolinguals have also reported negative or null results when it comes to positive effects of bilingualism on cognition (Kirk et al., 2014; Paap et al., 2016, 2017; von Bastian et al., 2016). Consequently, it has been suggested that a part of the discrepancies stem from the the way in which bilingualism is operationalised. In turn, it has been suggested that binary comparisons between bilinguals and monolinguals are insufficient to reveal specific effects of bilingualism on cognition (Luk & Bialystok, 2013).

Such binary comparisons presuppose that the mere fact that someone speaks two languages (as opposed to someone who does not) is deterministic and stable enough to distinguish two groups based on general cognitive processes which are necessary to control for two language systems (Leivada et al., 2021). In fact, however, the general cognitive processes used to control for two languages are far from stable in bilinguals themselves. In reality, bilinguals differ vastly from each other, for instance in terms of the timing, purposes, intensity, and quality of their bilingual language use across their lifespan (Beatty-Martínez & Dussias, 2018; Kroll et al., 2015; Pot et al., 2018). By way of example, an interpreter uses both languages under very different circumstances compared to a person who uses a foreign language to communicate with his/her foreign partner and in-laws. The cognitive challenge and therefore the cognitive processes needed to handle two languages would be very different in these two examples. Thus, it is reasonable to expect that the cognitive consequences of bilingualism in interpreters will differ from those in a person who is in a bilingual marriage. Yet, both individuals in my examples could be referred to as bilinguals and as such would be included in the same sample in a study which conceptualises bilingualism as a binary variable. Monolinguals are not a monolithic group either. Some monolinguals label themselves this way even though they have some knowledge of a second language (Gollan et al., 2002; Pliatsikas, 2021). Moreover, even in the genuine absence of any second language abilities, neurocognitive differences among monolinguals may still arise on the basis of the linguistic diversity in the environment they inhabit (Bice & Kroll, 2019). For these reasons, calls have been made to move forward focusing on the individual experiences *within* bilingual groups to determine *under which circumstances (if any) and to what extent* bilingualism affects the mind and, consequently, brain structure (Bak, 2016; Leivada et al., 2021). An important part of this advancement is the need to assess bilingual-related factors as continuous variables, rather than categorical ones (Luk & Bialystok, 2013), and to focus on the variability within bilinguals themselves with the view to identifying bilingual phenotypes (Navarro-Torres et al., 2021).

The next subsection will discuss some of the individual bilingual factors which have already been studied with respect to their effects on executive function. The focus will lie predominantly on studies which treated bilingual experiences as continuous variables, akin to the prevailing opinion on how the field should advance (Champoux-Larsson & Dylman, 2021; DeLuca et al., 2019; Luk & Bialystok, 2013).

1.2 INDIVIDUAL BILINGUAL FACTORS AS POSSIBLE MODULATORS OF EXECUTIVE FUNCTIONS

1.2.1 AGE OF LANGUAGE ACQUISITION

One of the notions on age of acquisition is that earlier acquisition of a second language should impact executive control more due to the relatively longer training of the ability to manage two languages (de Bruin, 2019). This has been tested in studies that investigated differences in executive functions, either between early and late bilinguals or using age of acquisition as a continuous variable. Some of these studies showed that early bilingual individuals performed better than late bilinguals on executive function tasks (Bdaiwi & Al-shujairi, 2015; Kapa & Colombo, 2013), and that earlier age of acquisition was related to a smaller conflict effect on an inhibitory control task (Soveri et al., 2011). At the same time, another study found that early and late bilinguals perform similarly on an attention task (Pelham & Abrams, 2014). This invited the view that in bilinguals who did not acquire the L2 early in life, their first language is more consolidated, making it harder to inhibit. It has also been suggested that late bilingualism might better train inhibitory control, whereas early bilingualism might bestow more training in switching (Bak et al., 2014) or conflict monitoring (Tao et al., 2011). Noteworthy is that age of acquisition did not emerge consistently as a significant continuous predictor of performance on a variety of executive function tasks (von Bastian et al., 2016).

The contradictory findings with respect to group differences could be further ascribed to the ambiguous cut off points of who are considered late or early bilinguals across studies (de Bruin, 2019). Moreover, the onset of language acquisition does not provide information about involvement of cognitive control processes during the course of bilingual language acquisition and use, which brings into question the use of this variable as a predictor of cognitive modulations (Leivada et al., 2021). Furthermore, age of acquisition confounds with another bilingual factor: language proficiency.

1.2.2 LANGUAGE PROFICIENCY

It has been proposed that high proficiency in two languages is at least in part an outcome of extensive experience in controlling the activation of the mother tongue (Kroll et al., 2021), which justifies a link between proficiency and cognition. In line with this view, Singh and Mishra (2012), for instance, have shown that bilingual children with a better command of the second language have perform better in terms of inhibitory and monitoring skills on an oculomotor version of the Stroop task. However, other studies on young and elderly adults did not report language proficiency to yield any significant effects on cognition (Mishra et al., 2019; von Bastian et al., 2016).

When assessing language proficiency, one often compares the individual level of mastery of a second language with the codified form of that language. An argument against the view of language proficiency as a prominent factor modulating cognitive control is that if any cognitive effects stem from the competition of language systems in one’s mind, the level of competition is not solely dependent on how well the internalized language resembles the codified version of that language (Leivada et al., 2021). On this note, Valian (2015) points out that if language proficiency had a prominent role in modulating cognitive capacities, interpreters, who are exceptionally proficient, should consistently outperform other bilinguals. This is often not the case, however, as will become more apparent in the following section. Overall, the effects of language proficiency on cognitive control, whether they can be ascribed to this variable alone or to its confounds, remain unclear. Therefore, studies which do not primarily focus on effects of proficiency on cognition should likely control for this variable in their designs.

1.2.3 PROFESSIONAL BILINGUAL EXPERIENCES: INTERPRETING AND TRANSLATING PRACTICES

Interpreters and translators are bilinguals with a high proficiency in both languages and can be both early or late bilinguals. However, these qualities do not make them distinct from a variety of other bilinguals. Rather, the factors which distinguish translators and interpreters from other bilinguals as well as each other emerge when considering how professionals regulate their languages on a daily basis in their jobs (Henrard & Van Daele, 2017).

Interpreters need to keep both languages strictly separated to allow for flawless monolingual production while, sometimes simultaneously, listening to a stream of speech in the other language. This behaviour has been assumed to require superior cognitive control and working memory, in no small part due to the immense time-pressure under which interpreters need to operate (Yudes et al., 2011). Translators are spared from the time-pressure and simultaneity of language production and comprehension in different languages. Nevertheless, their work routine consists of constant switching between both languages as they read and produce a translation in a limited time window. They also need to avoid interference and make sure that the translated text complies with the formal standards of the goal language and conveys the semantic and aesthetic message contained in the source text (Liparini Campos, 2015). It should be clear that professional bilingual practices cannot be easily conflated with experiential phenotypes of non-professional bilingual groups using mainstream bilingualism-related factors.

One possible view on the cognitive control processes underlying interpreting and translating practices is that they are not qualitatively different from those used by non-professional bilinguals to regulate their language use. The only difference would then be that professional bilinguals use these processes more intensely (Babcock & Vallesi, 2017). Indeed, several studies offer indirect supporting evidence for this view (Becker et al., 2016; Henrard & Van Daele, 2017; Woumans et al., 2015). For example, interpreters outperformed unbalanced bilinguals (i.e., bilinguals with unequal proficiency in both languages) and monolinguals on an inhibitory task (Simon task) and attention task (Attention Network test; ANT) (Woumans et al., 2015). Interpreters were also found to have an advantage over translators on a switching task as well as a dual task which taps into ability to carry out two tasks simultaneously (Becker et al., 2016). By contrast, other studies showed that interpreters did not perform better on the Simon task and ANT than balanced bilinguals did (Woumans et al., 2015), nor did they show an advantage in conflict resolution and switching advantage compared to matched multilinguals (Babcock & Vallesi, 2017). Some studies even failed to find an advantage in interference suppression and reactive inhibition in interpreters compared to monolinguals (Van der Linden et al., 2018; Yudes et al., 2011).

One key reason for these discrepant findings could be that the studies discussed use bilingual groups rather than assessment of bilingual experiences on a continuum. As mentioned earlier, such comparisons have important limitations, as one can unwittingly sample substantially heterogenous participants within one group (Soveri et al., 2011).

1.2.4 INTERACTIONAL CONTEXT

The interactional context in which bilinguals learn and use their languages is recognised to have an impact on bilingual language control. This claim stems from the assumption that some environments encourage or discourage specific language use. This idea is central to the Adaptive control hypothesis (ACH) (Green & Abutalebi, 2013). The ACH is a framework to depict how various social environments may lead bilinguals to use different cognitive control strategies such as goal maintenance, conflict monitoring, interference suppression, and response inhibition. The authors distinguish between three different interactional contexts: (i) the single-language context where only one language is used in one environment and another one in a distinct other environment; (ii) the dual-language context, in which both languages are used depending on the topics, situations or speakers, and where code-switching can occur, but usually only between sentences; and (iii) the dense codeswitching context, which refers to environments where bilinguals can alternate freely between languages and also mix them within one sentence.

These contexts differ in terms of the language control capacities they require. According to the ACH, the dual-language context is hypothesised to pose the highest demands on conflict resolution and interference suppression as one of the languages should be suppressed completely when the other one is used. Goal maintenance is important in this context due to speakers' need to establish and maintain the use of the language that is appropriate to the situation. Similarly, a bilingual who operates mostly in single language contexts needs to keep using the same language and suppress their other language. However, for a bilingual in the single language context, the maintenance of the target language and the interference of the other one is less cognitively demanding than in the dual language context, because the two languages are usually spoken in distinct environments. The dense code-switching context is posited not to trigger goal maintenance or conflict monitoring and interference control processes. The employment of these control processes stems from the competitive relationship between two languages, whereas during dense code-switching, the languages carry a cooperative relationship.

Many studies adopted the ACH framework to study the impact of the participants' interactional context on cognitive control. Whereas some studies have confirmed hypothesised effects of interactional contexts on cognitive control as proposed by ACH (Beatty-Martínez et al., 2019; Hartanto & Yang, 2016), others revealed more complicated patterns. For example, Ooi and colleagues (2018) compared conflict resolution performance of bilinguals in dense code-switching contexts among communities in Singapore, with bilinguals in single-language contexts in Scotland. The authors used the ATN, among other measures (Fan et al., 2002). Their results revealed that bilinguals in dense code-switching contexts outperform the single-language context bilinguals in conflict resolution. These results contradict the prediction of the ACH that dense code-switching contexts should not lead to an advantage in conflict resolution.

A possible reason for this discrepancy may stem from the fact that Ooi et al. distinguished their bilingual groups based on the environments they live in. It is possible to agree with the assumption that code-switching will be more prevalent among bilinguals in Singapore than among bilinguals in Edinburgh based on studies of these linguistic environments (Lauchlan et al., 2013; Xie & Cavallaro, 2016). However, such an approach may be insensitive to more subtle differences between individual language practices within each group. These concerns appear justifiable if one takes into consideration studies focussing on various types of code-switching and their effects on executive functions (Green & Wei, 2014; Hofweber et al., 2016; Kuzyk et al., 2020). These suggest that code-switching occurs in various qualitatively distinct forms that pose different demands on cognitive control.

1.2.5 HABITUAL CODE-SWITCHING PATTERNS

As could be derived from the discussion on the ACH, a possible distinguishing factor of code-switching patterns is whether switches occur between two sentences (intersentential) or within a single sentence (intrasentential). A framework devised by Muysken (2013) further distinguishes among four intrasentential code-switching types based on the patterns of how lexical and grammatical units from two languages are embedded in a single sentence. In insertion, words from one language are inserted in a matrix structure of the second language. In alternation, switches from one language to another one occur for a longer stretches. In congruent lexicalisation, also labelled *dense code-switching,* e.g., Hofweber et al., 2020b), lexical and grammatical items from both languages are intermixed. Finally, backflagging refers to a switch occurring after a discourse marker.

It has been assumed that these different types of code-switching employ different cognitive processes. For example, the Control Processing Model of Code-switching (CPM; Green & Wei, 2014) distinguishes between two modes of coordination in the mental representation of bilinguals: competitive and cooperative coordination. Under competitive coordination, only one of the languages can be used in a given context, while the other must be inhibited, thus requiring inhibitory control. A classic example would be a person who uses one language at work and another language at home. This mode aligns with the single language context as proposed by the ACH. For cooperative coordination, two qualitatively different variations are proposed: *open control and coupled control.* These types of control mode are likely to occur in the dual language and dense code-switching context. The open control mode enables execution of dense code-switching and according to the CPM, languages controlled in this mode stay co-activated, so they do not get inhibited. The coupled control mode relates to insertion and alternation, during which bilinguals rely on both inhibitory control and code-switching to regulate the two languages.

The coupling of insertion and alternation does not take into consideration the scalar hierarchy of code-switching types as proposed by Muysken (2013). Rather, it emphasises that these code-switching types enable successful code-switches through the use of the same cognitive processes. If anything, the time during which inhibition is needed to suppress the unwanted language, differs between alternation and insertion and the duration of sustained inhibitory control appears to determine whether a proactive or reactive control mode is employed (Criaud et al., 2012). Thus, it is worthwhile to consider whether these two code-switching types could also have different consequences for cognitive control. Treffers-Daller considered in her Inhibitory Continuum Model (ICM, Treffers-Daller, 2009) distinct engagement of cognitive control processes for all intrasentential code-switching types. She hypothesised that intarasentential code-switches can be positioned on a continuum according to the level of separation between the languages and posits a positive relationship between separation and the level of inhibitory control required to enable the switch. This model will be discussed in more detail in Chapter 4. Empirical studies on the link between specific code-switching patterns and cognitive control performance provide support for the notion that habitual code-switchers are better at those aspects of cognitive control that are trained by their code-switching behaviour (Hofweber et al., 2016, 2019, 2020b; Kuzyk et al., 2020). Such findings further highlight the need to consider code-switching types as modulators of executive functions, which will be further discussed in Chapter 4.

1.2.6 PROPORTIONALITY AND DIVERSITY OF LANGUAGE USE

The individuality of the bilingual experience is associated with the individuals' needs and uses of the languages. In this respect, one straightforward measure that could predict cognitive control demands is the frequency of use of both languages. Yamasaki and colleagues (2018) report that more frequent use of the second language was related to faster inhibition of distracting information in an attentional blink task, suggesting high frequency of use of both languages involves higher degrees of inhibitory control.

Grosjean (2015) points out that that language use needs could be domain specific as bilinguals acquire and use different languages for different purposes. Grosjean proposed to quantify the degree to which some topics and activities are used in both or only in one of the languages, hypothesising that this has cognitive consequences for the regulation of both languages (Grosjean, 2015). A diverse, more interchangeable use of both languages is assumed to trigger higher uncertainty as to what language should be used. The social diversity in bilingual language use can be captured by the measure of e*ntropy* (Gullifer & Titone, 2020). If a bilingual uses both languages in the same situations (high entropy), their cognitive system needs to be prepared to switch between and inhibit one of the languages very often, prompting reliance on proactive control. In contrast, bilinguals that show a clear separation of the situations in which they use L1 from the ones in which they use L2 (low entropy) are more likely to rely on reactive inhibition (Hofweber et al., 2020a). Using the measure of entropy as a predictor, (Gullifer & Titone, 2021) report that high entropy language use was indeed linked to better performance on a flanker task variation involving proactive control, with low entropy language use relating to more efficient reactive inhibition.

1.2.7 INTERIM SUMMARY OF EFFECTS OF BILINGUALISM ON COGNITION

On the face of it, it can seem that the question of what effects bilingualism has on cognition is hard to answer. However, it is important to realise that such a broad framing of the question does little justice to the rich characterisation of bilingual factors which has been established. In fact, aims of studies on the individual elements of bilingual experiences are largely not to pinpoint the main effect of bilingualism on cognition. Rather, they intend to identify which bilingual experiences and individual differences influence cognition in similar ways, giving rise to meaningful and consistent effects (Navarro-Torres et al., 2021). In other words, the questions asked in the literature reviewed here are often knowingly concerned with specific bilingual factors and their specific effects on cognition. Therefore, negative results observed should be interpreted in light of the question asked, rather than extrapolated to more general claims that main effects of bilingualism are non-existent.

Although the bilingual factors under study might be concrete and specific, they do not act alone. As pointed out, for example, proficiency and age of acquisition interact. Similarly, even though proficient bilinguals have specific modi operandi in their jobs, individuals within these groups also differ from each other in terms of proficiency or frequency with which they use both languages. Such an interaction of factors constitutes a scientific challenge which has been risen up to by devising more holistic measures and indicators tapping into an array of interrelated factors, such as entropy or interactional contexts which bilingual inhabit. However, it is necessary to keep advancing our understanding of bilingual effects on both levels: on the broader, holistic level, but also on the level of specific, individual bilingual factors. For example, effects of specific code-switching types on cognition in various interactional contexts can help us better understand the range of bilingual behaviours that typically occur in the given socio-cultural environment. Such knowledge can inform us on how to characterise bilinguals into groups with behavioural profiles in which comparable adaptive changes induced by their behaviours occur[2].

To understand the consequences of bilingualism in their entirety, it is necessary to explore not only the variability of this phenomenon itself, but also various research methods and tools to study it (Navarro-Torres et al., 2021). For example, Kroll and Bialystok (2013) pondered that

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[2] For such a characterisation of bilinguals based on their habitual community practices, the term *bilingual phenotyping* has been used (Navarro-Torres et al., 2021).

combinations of executive function tasks and measures of the neural mechanisms underlying the cognitive control used during completion of these tasks may shed more light on the actual cognitive demands which sometimes cannot be revealed behaviourally (for examples of reasons for this see Bialystok, 2016; Soveri et al., 2018). Indeed, functional neuroimaging has shown that individuals with comparable behavioural performance might still differ in the levels of recruitment of neural resources to execute a given task (see Pliatsikas & Luk, 2016 for a review). Moreover, studying neural consequences on the structural rather than functional level can circumvent the usage of cognitive tasks altogether (Leivada et al., 2021). Given that all cognitive adaptations induced by bilingualism are subserved by our brains, it is necessary to be au fait with the structural brain changes bilingualism brings about to deepen our theoretical understanding of bilingualism-related effects. However, as will become clear in the following sections, evidence from structural imaging might be harder to parse than one might think.

1.3 EXPERIENCE-DEPENDENT NEUROPLASTICITY

It has been widely established that the brain is a highly plastic and adaptable organ. The ability of our brains to change is a crucial part of our healthy ontogenesis, forming us into unique individuals and helping us to achieve our goals effectively (Lindenberger et al., 2017). Brain alterations occur when we face influential changes in our environment, after a brain injury or disease, when we must increase the efficiency of our behavioural endeavours, or during acquisition of a new skill (Famitafreshi & Karimian, 2019). As for the latter, the acquisition of demanding skills poses new challenges for cognitive processes necessary to solve the emergent tasks. This creates a mismatch between the functional supply of the brain structure and the experiential higher demands for the skill at hand (Wenger & Kühn, 2021). This mismatch triggers the creation of new dendritic spines leading to volumetric growth of structures responsible for the given task and enabling the relevant brain regions to respond to the altered environmental demands effectively (Wenger et al., 2017). The ability of the human brain to adapt to the cognitively demanding process of acquiring and mastering a new skill is termed experience-dependent neuroplasticity (Lövdén et al., 2013).

Three basic principles are critical in experienced-based neuroplasticity (Kleim & Jones, 2008): (i) for an experience to trigger structural brain changes, the increased cognitive demands must be high enough to exceed the possibilities of the existing neural resources; (ii) the duration and continuity of such experiences are co-determining factors for the changes to occur, and for the time-course within which they happen[3]; and (iii) the changes occur in brain areas which subserve our behaviour relevant for the task at hand.

These principles have been repeatedly confirmed in animal research (Crawford et al., 2020; Mesa-Gresa et al., 2021; van Praag et al., 2000) and in human studies which used structural brain imaging, comparing brain architecture before and after engagement in a new or newly demanding experience (De Sousa Fernandes et al., 2020; Teixeira-Machado et al., 2019; Wu et al., 2020). For example, London taxi drivers have been reported to have an enlarged region in the posterior hippocampus, which was linked to them maintaining and continuously navigating an elaborate mental map of the city (Maguire et al., 2000; Woollett & Maguire, 2011). As another example, it has been shown that learning how to juggle for three months can elicit expansion in structures responsible for complex visual motion (e.g., temporal lobe and intraparetic sulcus; Draganski et al., 2004). Further evidence of experience-related grey matter increases in the relevant brain areas comes from a variety of other populations including medical students (Draganski et al., 2006), mirror readers (Ilg et al., 2008), musicians (Granert et al., 2011; Groussard et al., 2014; Wenger et al., 2021), and, crucially, bilinguals (Mårtensson et al., 2012).

If one considers the above-mentioned basic principles of neuroplasticity, it is perhaps not surprising that bilingualism is often seen as one of the instances of human behaviour linked to increases in relevant regional brain volumes. As has been extensively demonstrated in the previous section of this introduction, bilingualism is a cognitively demanding experience. Moreover, it is usually a life-long experience, in which people engage continuously, and which often implies requirements for increasing efficiency to allow for steadily more fluent communication and growing language proficiency.

The next section will discuss evidence linking bilingualism with experienced-based neuroplasticity. In line with the above-mentioned principles of neuroplasticity, the following section will first briefly present the brain regions that have been implied to handle the cognitive control related to bilingual language use, with a special focus on the subcortical structures which

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[3] Cognitive intensity and duration of the experience interact. For example, very demanding experiences can trigger changes after several days of training. On the other hand, execution of a routine which is not experienced as very demanding can still lead to observable changes but sometimes after years. Thus, the time course in which observable changes (using traditionally magnetic imaging) occur can differ based on the intensity of the experience (Wenger & Kühn, 2021).

are of main interest to the current project. Subsequently, close attention will be paid to subcortical brain changes induced by individual experiences that have been presented previously as modulators of cognitive control demands.

BRAIN REGIONS INVOLVED IN MENTAL CONTROL OF TWO LANGUAGES

The first part of this thesis presented evidence linking bilingual language use to increased cognitive control demands. The various tasks discussed have also been used in growing numbers in studies focusing on the recruitment of neural systems of cognitive control in bilinguals (Pliatsikas & Luk, 2016). Using predominantly functional magnetic resonance imaging (fMRI), a number of regions and pathways in the brain have been identified to be affected by the use of bilingual language. In line with the notion that bilingual language control is subserved by domain-general executive functions, brain activation linked to language control typical for bilingualism has been observed in brain structures and networks which typically underlie cognitive control (Anderson et al., 2018a; Garbin et al., 2010). These regions span cortical structures, including the inferior frontal gyrus (IFG) and anterior cingulate cortex (ACC), as well as an array of subcortical regions (Pliatsikas, 2019). Given the principles of experience-dependent neuroplasticity (Lövdén et al., 2013), these regions subserving the highly demanding cognitive control processes during bilingual language use are also potential targets for expected structural adaptations. The brain regions which have been affected by bilingualism, likely by virtue of their involvement in bilingual language processing and control, are illustrated in Figure 1 (Pliatsikas, 2019). Numerous studies suggest the basal ganglia and the thalamus are critical for the efficient execution of cognitive control related to bilingual language use (Green, 2018; Hervais-Adelman et al., 2018; Stocco et al., 2014). Given the scope of the research comprising this thesis, these subcortical regions will be the main focus of the remainder of this chapter.

The basal ganglia consist of the caudate nucleus, putamen, globus pallidus, substantia nigra, nucleus accumbens, and subthalamic nucleus which are assumed to be the gatekeepers of neural signals to the cortex. In this view, the basal ganglia are responsible for rule selection in reaction to momentary circumstances and inhibiting habitual responses executed in the cortical regions (Green, 2018).For instance, the caudate nucleus is richly interconnected with IFG and the cerebellum, and regulates the execution of inhibitory control of these regions, together with the subthalamic nucleus (Wu et al., 2021). As such, it is also the key structure in language switching and the selection of language systems which are to be activated under specific conversational circumstances (Hervais-Adelman et al., 2015b; Stocco et al., 2014). The putamen subserves phonological control and processing, including the employment of language-specific articulatory motor programs (Abutalebi, Della Rosa, et al., 2013). It is also involved in the regulation of simultaneously executed processes, which is of particular importance to interpreters (Hervais-Adelman et al., 2015b; Hervais-Adelman & Babcock, 2020). The thalamus is another crucial subcortical structure which is richly connected with the basal ganglia and cortical regions such as IFG. It has been implicated in highly demanding executive control processes, language production and lexical selection (Ramezani et al., 2020; Yuan et al., 2021).

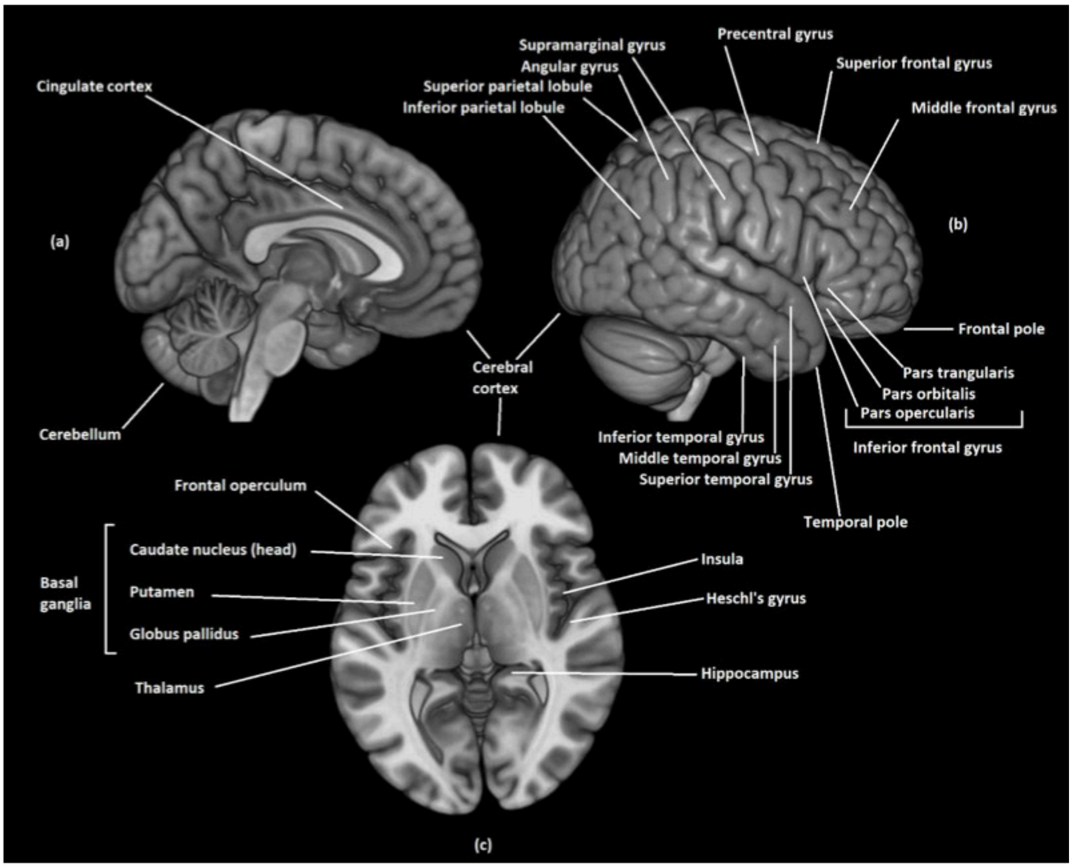

Figure 1. Grey matter regions which are involved in language control and processing.

Adapted from "Multilingualism and Brain Plasticity" By C. Pliatsikas, 2019. In J. Schweiter (ed) The Handbook of the Neuroscience of Multilingualism. Wiley Blackwell.

1.4 STRUCTURAL BRAIN ADAPTATIONS IN BILINGUALS

1.4.1 BILINGUALS VS MONOLINGUALS

Similar to the effects of bilingualism on cognitive control at the behavioural level, effects of bilingualism on brain structure have been reported by numerous studies comparing bilinguals with monolinguals. Bilinguals were found to have higher grey matter volumes or density relative to monolinguals in a variety of language- and cognitive control-related regions including bilateral caudate nucleus, and putamen (Burgaleta et al., 2016; Del Maschio et al., 2018; Legault et al., 2019; Mechelli et al., 2004; Olulade et al., 2016; Zou et al., 2012).

For example, one study comparing simultaneous bilinguals (i.e., bilinguals who acquired two languages simultaneously early on in their lives) with monolinguals revealed expansions of right caudate, left globus pallidus and bilateral putamen, as well as thalamus, in the bilingual group (Burgaleta et al., 2016). In another study, a similar but more complex patterns emerged. Pliatsikas and colleagues (2017) compared monolinguals with two groups of bilinguals with comparable L2 proficiency which were categorised based on bilingual immersion. That is, they were grouped as immersed or non-immersed, based on the time they have lived in a country where their L2 was spoken. The comparisons of the immersed group against monolinguals revealed pronounced structural effects in putamen, right thalamus, and globus pallidus. Conversely, comparisons of monolinguals with the non-immersed bilinguals revealed structural changes in bilateral caudate, an effect which was absent for the immersed group. The authors concluded that the caudate nucleus might be more important during the early stages of bilingual language acquisition.

Taken together, these group comparisons between bilinguals and monolinguals appear complicated to reconcile, and mixed results might emerge when accounting for a variety of other bilingualism-related variables. Thus, it has been suggested that investigation of structural changes related to individual bilingual factors within the group of bilinguals might shed more light on the variability of results (DeLuca et al., 2019).

1.4.2 INDIVIDUAL BILINGUAL FACTORS AND THEIR EFFECTS ON BRAIN STRUCTURE

1.4.2.1 AGE OF ACQUISITION

Although the ability of the human brain to adapt is preserved throughout our lifetimes, the extent to which the brain can change its structure varies depending on a series of developmental phases (Crone & Ridderinkhof, 2011). For language acquisition, a sensitive period between 0-7 years of life is assumed, during which the relevant brain structures are more plastic, enabling native-like levels of language knowledge, e.g., in terms of accent production, phonemic perception, and syntax (Hernandez et al., 2021). Therefore, it has been proposed that neuroplasticity in bilinguals with different ages of acquisition might manifest differently (Berken et al., 2017).

Studies controlling for age of second language acquisition have shown complicated patterns with both larger and smaller magnitudes of grey matter metrics in early bilinguals compared to late bilinguals, and similar results were found when assessing age of acquisition on a continuum (for a review, see Claussenius-Kalman et al., 2020). With respect to subcortical volumes, earlier age of acquisition has been related to larger volumes of subcortical regions responsible for general and bilingual cognitive control such as putamen and caudate nucleus (Berken et al., 2016; Legault et al., 2019; Wei et al., 2015). Assessment of age of acquisition as a continuous measure emerged as a positive predictor for expansion in the left accumbens and bilateral thalamus (DeLuca et al., 2019). By contrast, several other studies have not observed any isolated effects of onset of second language acquisition on grey matter structure, including the subcortical regions (Abutalebi et al., 2015; Felton et al., 2017; Pliatsikas et al., 2017).

In sum, the exact manifestation of age of language acquisition in structural brain adaptations remains unclear. Age of acquisition is not a clear-cut measure, and it likely gets more complicated to isolate the variance in structural changes related to the time when a language is acquired, the further in the past it resides. Furthermore, a very recent study conducted on 2/3 million participants has brought the hypothesised cut-off of the sensitive period for language acquisition under fire (Hartshorne et al., 2018). The authors revealed that the window of opportunity to acquire native-like levels of second language syntax does not close until late adolescence (i.e., 17 years). Such findings underline that the neurocognitive effects of language acquisition are still not fully understood and warrant further empirical investigation.

1.4.2.2. LANGUAGE PROFICIENCY

Within late bilinguals, better performance in pronunciation of the second language was linked to higher grey matter density in the left putamen, a structure assumed to subserve articulatory control (Berken et al., 2016). Within a group of balanced bilinguals, more extensive second language vocabulary was positively related to caudate volumes (Hosoda et al., 2013). Language proficiency has also been studied in interaction with age of acquisition (Hervais-Adelman et al., 2018). Controlling for age, higher second language proficiency was linked to larger subcortical volume of bilateral caudate, and this effect was stronger for proficiency than for age of acquisition (Hervais-Adelman et al., 2018). However, studies which kept language proficiency constant and varied other bilingualism-related factors, revealed structural differences which by virtue of the study design could not be ascribed to language proficiency (Deluca et al., 2019; Pliatsikas et al., 2015). This implies that bilingualism-induced brain plasticity goes beyond variation in language proficiency. In this vein, a recent study reported significant effect of language proficiency only in combination with second language exposure (Gallo et al., 2021).

Similarly to age of acquisition, the inconsistency of effects of language proficiency may occur because this variable is not static. Recall that in the context of experienced-dependent neuroplasticity, brain structural changes are related to the intensity and length of experiences. However, it is important to realise that proficiency itself is not an experience, but rather a product of variably intense and long bilingual experiences (Deluca et al., 2019). Furthermore, as mentioned in the previous section on the cognitive effects of language proficiency, this measure represents an indicator of how well a language system has been internalised relative to its codified version. It is reasonable to expect that the brain does not adapt primarily in response to an internal evaluation of how much the level of the second language resembles its codified form (Deluca et al., 2019). This highlights the limitation of the use of language proficiency as an experience-dependent factor when investigating bilingualism-induced neuroplasticity.

1.4.2.3 PROFESSIONAL EXPERIENCES

The available evidence on grey matter differences in translators and interpreters is very limited and to the best of our knowledge spans only four published studies (Becker et al., 2016; Elmer et al., 2014; Hervais-Adelman et al., 2017), only one of which focusing on subcortical structures (Elmer et al., 2014). Using cumulative hours of interpreting expertise as a predictor, the authors found positive correlations with caudate volumes (Elmer et al., 2014). By contrast, comparisons of simultaneous interpreters to non-professional bilinguals in the same study did not reveal any significant group differences.

Evidently, findings on neural effects of professional bilinguals are scarce, which prevents any resolute conclusions. Bilingual language use in professional interpreters and translators is distinct from that of non-professional bilinguals. At the same time, why and how professional bilinguals use their languages is arguably less variable than it is in non-professional bilinguals. This makes interpreters and translators an interesting target for the investigation of neuroplasticity brought about by relatively stable bilingual phenotypes.

1.4.2.4 EXPOSURE AND USE

Recall that research on the cognitive effects of bilingualism also considered bilingual language use and exposure. Notably, in the subchapter *1.2.5* of this thesis, code-switching habitual practices have been discussed as one of the language use patterns modulating cognitive control. However, to the best of our knowledge, no study to date have investigated structural neural correlates of this bilingual behaviour. In contrast, there are several neural studies which viewed bilingualism-induced neuroplasticity as a consequence of changes in environmental demands and as a function of continued bilingual language exposure in different contexts (e.g., Claussenius-Kalman et al., 2021; P. Li & Jeong, 2020, for overview see Beatty-Martínez & Dussias, 2019).

According to the ACH, the recruitment of different cognitive processes are reinforced by increased engagement in various interactional contexts (i.e., dual, single, and dense code-switching context). This reinforcement leads to enhanced performance in activities which draw upon a variety of cognitive processes. By extension, the variable requirement of the range of cognitive processes will also have varied consequences for neuroplasticity of brain regions relevant for bilingualism. Specifically, the goal maintenance relied on in the single language context is linked to activation and subsequent adaptations in IFG. Bilinguals in dual-language contexts need at times to suppress one of their languages completely, but also often need to keep both their languages active. Thus, the dual-language context requires goal maintenance, conflict resolution, and inhibition, which could have structural impacts on prefrontal inhibitory control hubs (i.e., IFG and ACC) and subcortical regions such as caudate, putamen, and thalamus. The relative free language-mixing in the dense code-switching context draws upon opportunistic planning, which relies on

IFG, cerebellum and caudate. Again, in bilinguals predominantly experiencing this context, these regions are expected to adapt structurally as a result of increased cognitive reliance on opportunistic planning.

An example of a measure which taps into effects of environmental circumstances is immersion in the second language. In this view, the degree to which bilinguals experience dual language contexts is thought to reflect the opportunity to train the regulation and control of the native tongue, through intense exposure to the second language (Linck et al., 2009). A longitudinal study investigated the effects of bilingual immersion in bilinguals by comparing brain structure and function at two points in time which where three years apart (Deluca et al., 2019). During these three years, participants stayed in a dual language context, and it was expected that they would continue to become more bilingually immersed. The authors reported significant differences in functional and structural brain metrics despite the fact language proficiency did not meaningfully differ between the two measurement points. These findings suggest that although continued bilingual language use does not need to result in measurable enhancement of proficiency, it still has measurable effects on the brain. However, even though two bilinguals operate in the same interactional context for the same period of time, this does not guarantee that they will have been exposed to the second language with equal frequency and intensity. Thus, even immersion, when measured in isolation, can suffer from similar limitations as the other experience-based factors discussed so far.

In all, from the above can be inferred that the variation of the observed neural effects cannot be well captured by the investigation of single factors studied in isolation. This is in no small part because these factors will likely interact with each other, sometimes working together and enhancing any structural changes, and sometimes working in opposite directions (Leivada et al., 2021). In this view, the fact that two observed effects resemble each other does not necessarily mean that they have been caused by the same configuration of bilingual variables (Kroll et al., 2021). This underlines the need to model the relative contribution of experience-based factors and their interactions to unravel the sources of variance with respect to bilingual effects.

1.4.2.5 QUANTIFIED AND COMBINED BILINGUAL EXPERIENCES

One possible way to capture a complex phenomenon like bilingualism, which comprises a range of underlying factors, could be the use of composite scores of bilingual experiences (Freemantle et al., 2003; Mazziotta & Pareto, 2020; Watt et al., 2015). Provided that the construction of the composite score is well-explained and motivated, and it is used across multiple studies that also describe other characteristics of the investigated populations, this score can serve as a steppingstone towards identifying the variables having the most prominent effects while considering the contribution of other characteristics of the studied population(Becker et al., 2017). Importantly, bilingual composite scores and interactional quantifiers have already been used to investigate neurocognitive adaptations in bilinguals (Anderson et al., 2018b; DeLuca et al., 2019; Hervais-Adelman et al., 2018; Sulpizio et al., 2020).

One of these composites scores is *the Language and Social Background Questionnaire* (LSBQ), which contains questions on participants' language use including language switching, the history of language acquisition, self-reported proficiency, and proportionality of the use of both languages in various contexts and during different activities. Answers to the questions in the LSBQ are scored on a numerated Likert scale and entered into an overall factor score calculator (Anderson, et al., 2018c), which creates three thematically distinguished composite scores (i.e., home language use; language use in social settings, and language proficiency score) and one composite score subsuming all the information. Anderson et al. (2018c) investigated 408 bilingual participants and tested the reliability and validity of this questionnaire as an instrument to assess the degree of bilingualism.

The LSBQ questionnaire has been used in a recent within-bilingual study (DeLuca et al., 2020), using the LSBQ scores for home and social language use, age of acquisition, and the interaction of these three measures. The study reported expansions of left nucleus accumbens, caudate nucleus and right thalamus to be positively related to social language use but no significant effects were revealed with respect to language use in the home setting. Furthermore, the earlier onset of language acquisition was positively correlated to expansions and contractions in parts of right caudate nucleus and putamen, and to contractions in the thalamus and the nucleus accumbens. The authors interpreted these results to mean that structural changes vary depending on the degree of optimisation of bilingual language control in diversely experienced bilinguals. Such findings are consistent with the notion that bilingual experiences can variably modulate structural adaptations. Moreover, it highlights that modelling bilingual experiences on a continuum, using composite scores of bilingual experiences, is a way forward in unravelling the circumstances under which bilingual experiences confer systematic neurocognitive effects.

1.4.3 INTERIM SUMMARY OF BILINGUAL EFFECTS ON BRAIN STRUCTURE

Over the years, great efforts have been undertaken to identify which among the many possible modulatory factors of bilingual experiences lead to the most robust emergence of neurocognitive effects. Researchers investigated a diversity of bilingual populations, tested the contribution of individual experiences and categorised bilinguals into numerous groups according to a variety of experience-based criteria. So far, no specific categories or theoretically proposed phenotypes of bilingual groups have emerged from these efforts as consistently decisive causes of bilingualism-induced neural effects (Leivada et al., 2021).

In all, the paradigm-shift in the field towards the acknowledgment of the complexity of bilingualism and away from mere group comparisons brought a promise of more consistent results and a better understanding of bilingualism-induced neurocognitive changes. At the same time, considerable progress has occurred in terms of the neurobiological principles of experience-related brain adaptations. It is intriguing to explore how and whether these new advancements could help the field of bilingualism research to broaden understanding of the brain changes brought about by bilingualism. one potentially valuable theoretical model stems from the field of experience-dependent neuroplasticity: *the expansion-renormalisation model* (Wenger, Brozzoli, et al., 2017).

1.5 NON-LINEAR STRUCTURAL BRAIN CHANGES

It would be foolish to expect that the immense amount of knowledge and skills that humans acquire throughout their lives will lead to continuous increases of brain volumes. Such a view is also inconsistent with evolutionary principles which posit that nature's solution to efficient progress is not a never-ending growth, but rather the selection of the best candidates among many and elimination of the less suitable ones (Lindenberger & Lövdén, 2019; Wenger, Brozzoli, et al., 2017). This Darwinian concept has been an inspiration to the conceptualisation of neurobiological processes for many years (Berezin, 1978; Dehaene & Changeux, 1989), and has also recently crystallised within the field of experience-dependent neuroplasticity into *the expansion-renormalisation model* (Kilgard, 2012; Lindenberger & Lövdén, 2019; Lövdén et al., 2010, 2013, 2020; Makino et al., 2016; Wenger, Brozzoli, et al., 2017)[4].

According to this model (Figure 2), experience-related changes often follow a three-phased trajectory of expansion, selection, and renormalisation. First, the brain reacts to a newly emergent demanding task by expanding neuronal resources such as neuronal dendrites and synapses in structures responsible for the given task, which leads to an overall increase of the relevant regional brain volumes. Continuous practice in the new task creates opportunities for the brain to explore which of the newly built neural resources are most suitable and effective to achieve the targeted behaviour. On the behavioural level, the performance in the concerned task increases with training until it hits a ceiling of efficiency, after which it stabilises. Once the behavioural performance stabilises, the structural volumes in the related brain regions are posited to renormalise, sometimes even completely back to the levels prior to learning. This potentially reflects the changes on the microscopic level. Namely, among the expanded network of neuronal connections, the most efficient ones are selected, whereas the superfluous ones are eliminated through a process of so-called *synaptic pruning*.

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[4] Note that in the context of neural microcircuits, the equivalent of this model is called *The Exploration–Selection–Refinement Model* (Lindenberger & Lövdén, 2019; Lövdén et al., 2020).

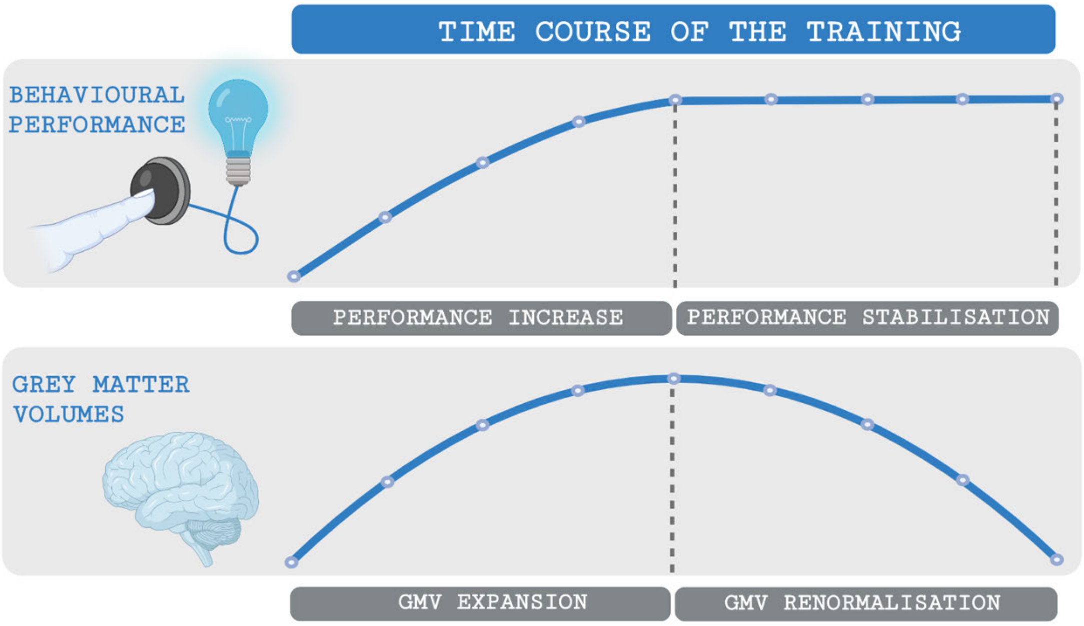


Figure 2. Expansion-renormalisation model (simplified; Wenger et al., 2017).

The illustration depicts the relationship between grey matter changes and behavioural performance.

(created with BioRender.com)

In all, skill acquisition may trigger a non-linear trajectory of initial volumetric increases of relevant brain structures, followed by their decreases as a behaviourally optimal neural circuitry is being selected (Wenger, Brozzoli, et al., 2017). This assumption of non-linearity has so far not been tested in efforts to reconcile the divergent effects of bilingual experiences on volumetric changes (but see Pliatsikas et al., (2020), which investigated age-related developmental non-linear trajectories in bilinguals). Nevertheless, if this principle holds for bilingualism, it could be incorrect to expect that increasing efficiency in bilingual language use should result in linearly corresponding increases of neural resources in the relevant brain regions. Recently, a model of bilingualism-related brain changes has been proposed which incorporated the assumption of non-linearity: the Dynamic Restructuring Model (DRM, Pliatsikas, 2020)

1.5.1 DYNAMIC RESTRUCTURING MODEL

The DRM brought together evidence from existing studies on structural brain changes in various bilingual populations with qualitatively and quantitatively different sets of experiences (Pliatsikas, 2020). It assessed the various bilingual factors and experiences which have been hypothesised to have effects on cognitive demands. The authors set forth three curious observations that helped give rise to the notion that structural adaptations related to bilingualism are dynamic.

First, bilinguals who had long-standing experience in bilingual language use and were using both languages frequently in their daily lives (i.e., immersed bilinguals) had similar patterns of structural changes irrespective of the onset of second language acquisition. Specifically, acquisition of the second language in early childhood did not leave different fingerprints on brain structure relative to immersed bilingual language use in later bilinguals. The similarity of effects was chiefly found in terms of the shape and volumes of subcortical structures including the thalamus (Burgaleta et al., 2016; Pliatsikas et al., 2017). Second, significant structural changes in cortical grey matter were reported predominantly in sequential bilinguals who were not immersed in bilingual language use and in elderly adults with a history of lifetime use of multiple languages (Luk et al., 2011; Pliatsikas et al., 2015). Third, grey matter reductions were observed in interpreters relative to non-professional bilinguals, even though interpreters' routines are marked by exceptional language control and switching demands (Elmer et al., 2014).

Indeed, these findings would support the notion put forward in the DRM that structural brain changes brought about by bilingualism are dynamic, likely following phases of increases and decreases throughout the bilingual experiential trajectory. The observed direction of these effects and their magnitudes will then likely differ depending on where on the trajectory someone is positioned with respect to second language learning and use. Ultimately, the DRM made the principle of expansion-renormalisation an integral component, proposing testable predictions of bilingualism-induced non-linear brain adaptations. The model proposes three stages during which qualitatively diverse structural adaptations of grey and white matter are observed depending on the duration, intensity and quality of exposure to the second language.

During *initial exposure*, vocabulary learning and the need to control between lexical alternatives for the same concepts bring new demands on cognitive control. This stage induces cortical grey matter changes in regions related to executive control and short-term memory, including prefrontal and frontal regions, as well as subcortical adaptations in hippocampus, and, importantly, the caudate nuclei.

The second stage, *consolidation,* is hallmarked by the achievement of a level of optimisation in learning new words and controlling for competing lexical alternatives. Concurrently, the grey matter adaptations described in the first stage stabilise, as indicated by the absence of effects in caudate nuclei and hippocampus in highly proficient bilinguals with prolonged engagement with both languages (Pliatsikas, 2020). At this stage, learning emphasis in bilinguals shifts to the differentiation of semantic and grammatical alternatives. Concurrently, they need to monitor situations in which to use a particular language, and if appropriate, suppress the unwanted language. These demands translate to adaptations in the cerebellum, basal ganglia and thalamus, regions involved in cognitive control.

The final stage, *peak efficiency*, predicts adaptations in the most experienced groups of bilinguals, e.g., interpreters. Efficient and automatic language control stemming from bilingual immersion results in maximally efficient connectivity and leads to increased cerebellar volumes. Importantly, the caudate renormalises at this stage, possibly even back to baseline levels. However, this stage has received less attention and it remains unclear whether also other parts of the bilingual brain continue adapting to changing demands or increasing efficiencies as a result of growing bilingual experience (Pliatsikas, 2020).

Consistent with the broader paradigm shift within bilingualism research, it is key to the DRM that structural brain adaptations are governed by dynamic and nuanced differences among bilingual experiences. However, while contemporary research has started to consider bilingualism-induced neuroplasticity in relation to nuanced differences in individual bilingual experiences, the DRM extends existing approaches and models by incorporating the assumption of non-linearity of neural adaptations. Specifically, it posits that bilingualism, like other demanding experiences, triggers complex but systematic patterns of transient expansions followed by renormalisation of regional brain volumes. This highlights a crucial change of perspective for future studies that encourages consideration of non-linearity in study designs. With the advent of appropriate analytical methods that help describe non-linear effects, recent work has already started successfully modelling dynamic relationships between behaviour and brain properties (Pliatsikas, 2021). By and large, these approaches offer the field of bilingualism research a valuable way to advance understanding of the neurocognitive impact of bilingual experiences.

1.7 OUTLINE OF THE THESIS AND OF ITS AIMS AND OBJECTIVES

This thesis aims to contribute to the explanation of inconsistencies found in previous studies on bilingualism-induced brain changes by testing predictions from the Dynamic Restructuring Model. For these purposes, I will leverage a rich set of structural brain imaging data of Czech-English bilinguals with comparable socio-cultural and linguistic backgrounds, advanced command of English, and a broad range of bilingual experiences. If bilingualism is indeed a demanding experience that can alter relevant brain structures, it is to be expected that the observed effects are non-linear and dependent on the quantity and quality of bilingual language use. Furthermore, the changes should occur in regions relevant to the cognitive demands, and the extent and trajectory of these changes should reflect the intensity of and ways in which both languages are used.

Study 1 explores the dynamic effects of combined bilingual experiences on subcortical brain structures. The study will test predictions of the DRM, including non-linear structural brain changes related to bilingual experiences of various quantities. We use a continuous, quantified, composite indicator of bilingual experiences (Language and Social Background Questionnaire; LSBQ; Anderson et al., 2018). The LSBQ serves as the key predictor of volumetric changes in the regions of interest across the entire sample. As such, this study aligns with existing research investigating structural brain changes using this very composite indicator of bilingual experiences, which will allow for comparison with results from other studies (Anderson, Chung-Fat-Yim, et al., 2018; DeLuca et al., 2019; DeLuca et al., 2020). Critically, study 1 expands methodologically on previous work by using generalised additive mixed models (GAMMs) (Pliatsikas et al., 2020; Pliatsikas, 2021), a statical methodology that can reveal non-linear volumetric trajectories (Wood, 2017).

Study 2 uses a similar approach as study 1 and expands on it by splitting the existing sample into three groups according to their professional bilingual experiences: interpreters, translators, and bilinguals without any professional experience (non-professional bilinguals). Again, the LSBQ bilingual composite scores are used as the main predictor of volumes of three subcortical structures that are particularly relevant for translating and interpreting practices, and for bilinguals in general: caudate and putamen. It tests the hypothesis that the intensity of bilingual experiences and their transformative power differs depending on the professional context within which languages are used. Nevertheless, it is assumed that professional bilinguals, while considered exceptionally skilled individuals in controlling for two languages, rely on the same neural substrates as their non-professional counterparts. The repeated use of composite scores capturing general bilingual experiences allows us to determine whether the trajectories of the volumetric changes differ between groups. As such, this study will test whether quantity (as revealed by the LSBQ scores) and quality of bilingual experiences (as indexed by professional experience) have distinct effects on brain structure. The data are analysed using Bayesian Generalised Additive Models. Opting for Bayesian-driven statistics allows the comparison of the shapes of the trajectories between groups (Levshina, 2018).

Exploring experiences beyond the LSBQ composite scores can contribute to our understanding of what aspects of bilingual language use affect brain structure. Study 3 focuses on code-switching, a unique bilingual behaviour that has been shown to engage cognitive control processes (Blanco-Elorrieta & Pylkkänen, 2018). As detailed in this chapter, cognitive processes which subserve code-switching has been hypothesised in theoretical models either based on the control demands related to the interactional contexts in which it occurs (Green & Abutalebi, 2013) or based on control processes linked to various code-switching types (Green & Wei, 2014; Treffers-Daller, 2009). Although code-switching has been put forward as a potential key to understanding bilingualism-related effects on the brain and cognition (Blanco-Elorrieta & Pylkkänen, 2018; Costa et al., 2009; Leivada et al., 2021), its neural structural correlates have not been studied to date. Study 3 constitutes the first attempt to identify structural brain correlates of habitual code-switching patterns, considering the level of separation of both languages within the switch and its directionality. An ecologically valid code-switching frequency task with authentic Czech-English utterances as stimuli captures the usage frequencies of the various code-switching types, which serve as the main predictors of caudate and thalamus volumes. These two regions have been implicated in code-switching and differ in terms of the cognitive control processes they enable during bilingual language use. Study 3 focuses only on non-professional bilinguals to minimise observed variance from other sources than code-switching engagement. Translating and interpreting practices primarily rely on the same neurocognitive substrates as code-switching (Hervais-Adelman et al., 2015), and since this study aims to reveal structural correlates of a fine-grained, linguistic phenomenon, prominent professional experience would compromise interpretability. We investigate the relationship between code-switching habitual patterns and caudate and thalamus volumes using GAMMs.

The results and implications of the three studies are discussed in the context of existing literature in the General Discussion in *Chapter 5*. Here, we will also consider how the results advance our understanding of structural brain changes triggered by bilingual experiences. Finally, the ways forward will be outlined, arguing that viewing bilingualism through the lens of experience-dependent neuroplasticity will offer more complex but testable predictions of bilingualism-induced brain adaptations.

CHAPTER 2

BILINGUAL EXPERIENCES INDUCE DYNAMIC STRUCTURAL CHANGES TO BASAL GANGLIA AND THE THALAMUS

ABSTRACT

Bilingualism has been linked to structural adaptations of subcortical brain regions that are important nodes in controlling of multiple languages. However, research on the location and extent of these adaptations has yielded variable patterns. Existing literature on bilingualism-induced brain adaptations has so far largely overseen evidence from other domains that experience-based structural neuroplasticity often triggers non-linear adaptations which follow expansion-renormalisation trajectories. Here we use generalised additive mixed models (GAMMs) to investigate the non-linear effects of quantified bilingual experiences on the basal ganglia and thalamus in a sample of bilinguals with wide range of bilingual experiences. Our results revealed that volumes of bilateral caudate nuclei and accumbens were positively related to bilingual experiences in a non-linear pattern, with increases followed by decreases, in the most experienced bilinguals, suggesting a return to baseline volume at higher levels of bilingual experience. Moreover, volumes of putamen and thalamus were positively linearly predicted by bilingual experiences. The results offer the first direct evidence that bilingualism, similarly to other cognitively demanding skills, leads to dynamic subcortical structural adaptations which can be nonlinear, in line with expansion-renormalisation models of experience-dependent neuroplasticity.

2.1 INTRODUCTION

Mounting evidence in the past two decades has shown that the cognitively demanding experience of bilingualism affects brain structure (see for review Tao et al., 2021). Given that the majority of the world's population is bilingual (Marian & Shook, 2012), bilingualism-induced neuroplasticity constitutes an appealing candidate for investigating how long-lasting demanding cognitive skills and experiences affect brain morphology (Kroll et al., 2014). However, using knowledge about bilingualism-induced neuroplasticity to draw conclusions about experience-dependent brain adaptations has been hampered by inconsistent results from studies in the field. Namely, existing research often reports structural changes in different regions and effects in different directions, including both volumetric increases and decreases (Pliatsikas, 2020). While the field of bilingualism-induced neuroplasticity has generally embraced the basic assumption that demanding experiences can lead to neural adaptations, it has not examined the inconsistencies through the prism of general principles of experience-dependent neuroplasticity. In fact, experience-induced structural brain changes are often not linear, but rather dynamic, and they depend on the quality, quantity, and time course of experiences that trigger them (Lindenberger & Lövdén, 2019; Lövdén et al., 2013). Consequently, the exact dynamic nature of the effects of bilingualism on the brain might have remained overlooked. To address this issue, bilingualism needs to be approached as a continuous cognitively demanding experience, which can trigger dynamic structural adaptations.

The general brain mechanisms behind the acquisition of a new skill, such as learning a new language, resemble an audition (Lövdén et al., 2020). When facing a new cognitive challenge which cannot be met by the existing neural resources, brain expands to explore new candidates for efficient neural circuits to perform the newly emerged task. Upon selection of the most promising neural circuit resulting in required performance efficiency, the brain eliminates the superfluous neural resources. With respect to volumetric brain changes, the prominent theories argue for expansion-renormalisation model [Wenger et al., 2017; also see Lindenberger & Lövdén (2019) for *The Exploration-Selection-Refinement Model*]. According to it, initial volumetric increases related to skill acquisition are followed by decreases once the skill has been acquired and exercised efficiently. From this follows that cognitively demanding experiences often trigger brain adaptations that are not linear, but rather following an expansion-renormalisation trajectory.

Experience-depended neural adaptations are typically observed in brain regions which functionally support managing of the task at hand (Wenger & Kühn, 2021). In the case of second language learning (L2) and bilingual language use the critical regions are those subserving switching, cognitive and articulatory control, and language selection. Perhaps the most important of these regions are the basal ganglia (including structures such as caudate, putamen, globus pallidus and accumbens) and the thalamus (Green & Abutalebi, 2013; Li et al., 2014). In general, these structures subserve integration of information from multiple cortical areas to select purposeful action in response to external stimuli or internal cues (Simonyan, 2019). It has been shown that language switching and selection of appropriate language systems allowing bilinguals to achieve fluent communication draws upon the cognitive-general functionality of basal ganglia and thalamus (Green & Abutalebi, 2013). Specifically, several studies reported recruitment of bilateral caudate during language-switching, and vocabulary learning (Hervais-Adelman et al., 2015b; Luk et al., 2012; Ma et al., 2014; Van den Broek et al., 2013). The globus pallidus and putamen have both been reported to engage in phonological monitoring and selection (Liu et al., 2010),while the putamen has also been implicated in the employment of motoric control schemata linked to language-specific articulatory demands (Viñas-Guasch & Wu, 2017). Activation of the nucleus accumbens has been explained by its role in maintaining the motivation to learn the second language (DeLuca et al., 2019). The thalamus, a region extensively connected with basal ganglia, has been implicated in language selection and, together with the globus pallidus, it subserves the coordination of motor routines related to language-specific articulatory motor programmes (Abutalebi & Green, 2016; Ford et al., 2013; Grillner & Robertson, 2016).

Evidence from structural studies confirms that the basal ganglia and the thalamus adapt structurally following bilingual practices. However, existing studies presented seemingly scattered patterns of these adaptations, often reporting effects in different regions, in different directions, or even absence of some effects altogether (Tao et al., 2021). For example, compared to monolinguals, bilinguals have generally been reported the have larger caudate nuclei, putamen globus pallidus and thalamus (Abutalebi et al., 2013; Berken et al., 2016; Burgaleta et al., 2016) but these effects tend to disappear in bilinguals immersed in bilingual context (Pliatsikas et al., 2017). Perhaps more confusingly, *smaller* caudate volumes have been reported in long-standing interpreters, that is exceptional bilinguals using both languages professionally, when compared to individuals with less cumulative interpreting experiences (Elmer et al., 2014). These contrasting patterns have posed a challenge to the field in understanding the mechanisms that lead to bilingualism-induced adaptations.

Recall that a lot of this variability may be because of lack of understanding or systematic study of the dynamic nature of these adaptations. With respect to bilingualism, the Dynamic Restructuring Model (DRM) (Pliatsikas, 2020) builds on the expansion-renormalisation model (Lövdén et al., 2013) to conceptualise the bilingualism-induced brain changes. The DRM argues that in the case of bilingualism, structural brain adaptations are triggered by environmental changes in language control demands, which are determined by practices in bilingual language use and the amount of bilingual experiences. As such, the DRM offers a unifying theory explaining the divergent findings on brain changes brought about by bilingualism mentioned earlier.

We now turn to the specific predictions by the DRM on the regions of interest of the present paper, namely the basal ganglia and the thalamus. Individuals who start to learn a vocabulary of the second language face a new need to control between lexical alternatives for the same concepts. This assumedly triggers volumetric expansion of the caudate which subserves acquisition of new words in the second language (Van den Broek et al., 2013) and lexical selection and control (Green & Abutalebi, 2013). Once bilinguals become proficient in both languages and start to engage with both languages more often, the most efficient networks get selected among the newly built neural resources. In turn, the volumetric expansion of caudate will reverse over time. This explains the variability in results in the studies mentioned above; volumes of caudate increase in less experienced bilinguals when compared to monolinguals, but these effects are absent in highly proficient bilinguals (Pliatsikas et al., 2017). Highly proficient bilinguals face new cognitive challenges linked to increased language production and control, which poses greater demands on language monitoring and motor control related to articulation. This explains the findings of increases in regions implicated in articulatory control and phonological selection in more experienced bilinguals, such as the left putamen (Abutalebi, Rosa, et al., 2013; Berken et al., 2016) and globus pallidus (Burgaleta et al., 2016). Similarly, more experienced bilinguals have a likely richer vocabulary, which leads to the growing need for lexical selection during production. This can explain the expansion of thalamic volumes, which is assumed to enable a more efficient selection mechanism (Abutalebi & Green, 2016).

In light of the above, acquisition and use of two or more languages resembles other complex skills in that it requires lifelong reconfiguration of the behavioural repertoire to address the altering cognitive demands. The DRM posits that such a longstanding dynamic process such as bilingualism brings about dynamic, non-linear effects on brain structure and that specific bilingual experiences can predict these effects. These experiences have been suggested to include onset of the second language (L2) acquisition (Rossi et al., 2017), proportional usage of first (L1) and L2 (Del Maschio et al., 2020), duration of L2 use (Kuhl et al., 2016), L2 proficiency (Abutalebi et al., 2013, but see Deluca et al., 2019), linguistic differences between L1 and L2 (Ramanujan, 2019), and intensity of switching between the languages (Zou et al., 2012). Nevertheless, the DRM predictions remain formulated based on the synthesis of results from single studies which largely used between-groups comparisons (e.g. bilinguals vs. monolinguals). Such an approach cannot account for the variability in the aforementioned individual bilingual experiences. Instead, treating bilingualism as a continuous rather than categorical variable and looking at the variability withing a bilingual sample has been called upon as an alternative approach with a potential to contribute new insights in the effects of bilingualism on the mind and brain (Kroll et al., 2015; Luk & Bialystok, 2013).

Following from these suggestions, a recent study applied an experienced-based approach in revealing dynamic changes of neural adaptations in bilinguals (DeLuca et al., 2019). To quantify bilingual experiences, they used *the Language and Social Background Questionnaire* (LSBQ, Anderson et al., 2018c), which provides continuous measures of bilingual use in different contexts. DeLuca and colleagues reported expansions of left accumbens, caudate and right thalamus to be predicted by social language use, whereas age of language acquisition predicted both expansions and contractions in parts of right caudate and putamen and contractions in bilateral accumbens and thalamus. These results support the notion that bilingual experiences assessed on a continuum can reveal complex patterns of brain adaptations. Critically however, these analyses assumed *linear* structural adaptations. Treating effects of bilingualism linearly disallows for testing of predictions rooted in evidence that demanding experiences can have *non-linear* effects on brain structure. Therefore, it is crucial to allow for non-linearity of these effects in order to examine the evidence-based DRM predictions that changes brought about by bilingualism are dynamic.

In point of fact, prominent theories of experience-dependent neuroplasticity advocate *against* assuming linear brain volume growth during skill acquisition (for review, see Wenger et al., 2017), with some even calling assumed continual increase in brain volumes unfeasible (Azmitia, 2007). With respect to bilingualism, Pliatsikas and colleagues (2021) used Generalised Additive Mixed Models (GAMMs), a statistical method that can reveal non-linear effects, to study concentrations of brain metabolites in the basal ganglia as a function of bilingual experiences. Among other markers, they investigated concentrations of myo-Inositol (INS) and N-acetyl aspartate (NAA), which have been treated as markers of the processes that underlie neuroplasticity, such as synaptic pruning and repurposing of neural substrates. They revealed that bilingual experiences predicted these concentrations in a non-linear fashion. The authors interpreted this as indirect evidence for microscopic experience-based restructuring of the basal ganglia, signifying increases in synaptic connections and also the elimination of the superfluous synapses depending on the amount of bilingual experiences, an interpretation that is in accordance with the DRM.

However, it remains to be determined whether such non-linear adaptations observed on the microscopic level occur also at the level of volumes of relevant brain structures.

Following up from this approach, in the present study we employ GAMMs to model non-linear effects of continuous measures of bilingual experiences on volumes of basal ganglia and thalamus across a rich sample of bilinguals with a wide range of bilingual experiences. Specifically, our sample ranges from bilinguals with limited opportunity for active bilingual languages use, to advanced bilinguals and translators, who engage with two languages daily, to exceptional bilinguals such as interpreters, who face extreme control demands in their jobs. The dynamicity of bilingualism is captured on the continuum using the LSBQ composite score (henceforth in this chapter *Bilingual composite score; BCS*), which spans information about language proficiency, exposure, switching, and duration and proportionality of the use of both languages (Anderson et al., 2018).

Based on DRM, we predicted distinct trajectories of volumetric adaptations of basal ganglia and thalamus as a function of quantified bilingual experiences. Specifically, we expected an a expansion-renormalisation pattern of the caudate, expressed as a trajectory suggesting increases in volume with limited bilingual experience, which will however plateau and eventually decrease as bilingual experience increases. A similar pattern was also predicted for the neighbouring nucleus accumbens, a region that is strongly interconnected with the caudate nucleus and has also been shown to contract in experienced bilinguals (Deluca et al., 2019). According to the DRM, adaptations of putamen and globus pallidus have been suggested to come after the onset of caudal changes. With respect to the putamen, we expect to observe a pattern consistent with onset of structural brain adaptations in bilinguals with larger amount of bilingual experiences than for the caudate and the accumbens. If putamen will manifest renormalisation, we predict that this will occur only in individuals at the highest end of the spectrum of bilingual experiences. Globus pallidus has received less attention than the neighbouring putamen. However, we expect comparable patterns as in putamen due to the interrelatedness of both structures, and their shared functionality (Pliatsikas et al., 2017). Expansions of thalamus have been reported in long-standing, regularly practicing bilinguals whose brain has reached efficiency in the mechanisms that undertake vocabulary learning and control (DeLuca et al., 2019). It has been suggested to be involved together with globus pallidus in coordinating of motor programmes (Josephs et al., 2021), a function employed for successful articulation of different languages. Taken together, we expect to observe comparable adaptation patterns as in putamen and globus pallidus, i.e., later onset of thalamic volumes increases relative to caudate with possible renormalisation only in bilinguals with high level of bilingual experiences.

2.2 RESULTS

2.2.1 EFFECTS OF BILINGUAL EXPERIENCES ON VOLUMETRIC CHANGES IN LEFT AND RIGHT HEMISPHERE

In the first-level model using GAMMs, we examined whether bilingual composite scores had different effects on the left and right volumes of the ROIs. To do so, we examined whether BCS x Hemisphere interaction is reliably significant when its effects are tested for both left and right hemisphere as reference levels. The results revealed that the BCS x Hemisphere was reliable significant with both reference levels of hemisphere (see *Appendix A*). This suggested that effects of the BCS on each hemisphere of the globus pallidus may be significantly different. Therefore, in the subsequent second-level model (see next section), we split the globus pallidus data across hemispheres and examined effects of BCS in each hemisphere. For all other ROIs BCS x Hemisphere interaction did not emerge as a reliably significant predictor, so we collapsed the data across hemisphere for these structures at the second level analysis.

2.2.2 EFFECTS OF INDIVIDUAL BILINGUAL EXPERIENCES ON VOLUMES OF ROIS

The results from the second-level analysis are illustrated in Figure 3. BCS, the metric of interest, emerged as a non-linear predictor of caudate and accumbens volumes. Specifically, the results reveal a positive relationship between BCS and volumes in these two regions, but only to a certain level of bilingual experience after which the growth in volumes appears to reach a plateau for the accumbens, and start decreasing for the caudate (See Figure 3). BCS was also a significant linear predictor of putamen and thalamus volumes, in that the higher BCS, the larger volumes. Age emerged as a significant predictor for volumes of the caudate, the putamen, and the thalamus with smaller volumes as a function of age. The analysis also revealed a significant main effect of Hemisphere. The left accumbens and the putamen were larger than the right ones. Conversely for the caudate and the thalamus, the volumes of these structures in the right hemisphere were larger than in the left hemisphere. The two second-level models for each hemisphere of the globus pallidus showed that the BCS is not a significant predictor of globus pallidus volumes, in neither of both hemispheres (illustrated in Figure 4). The results from the second second-level models for structures collapsed across hemispheres can be found in Table 1.

Table 1. Results from GAMMs, second-level model.

Main effects of bilingual experiences (BCS), age and hemisphere on subcortical volumes of caudate, putamen, accumbens, and thalamus. Two separate models for each hemisphere for globus pallidus with bilingual experiences and age as main effects.

	caudate	**putamen**	**accumbens**	**thalamus**	**globus pallidus**	
					left	**right**
BCS	**<0.001***^**	**0.028***	**0.027*^**	**0.014***	0.693	0.236
Age	**0.003****	**0.022***	0.271	**0.047*^**	0.469	0.508
Hemisphere	**0.009****	**<0.001*****	**<0.001*****	**<0.001*****	-	-

Note: ^: edf>1.0, denoting a non-linear effect.

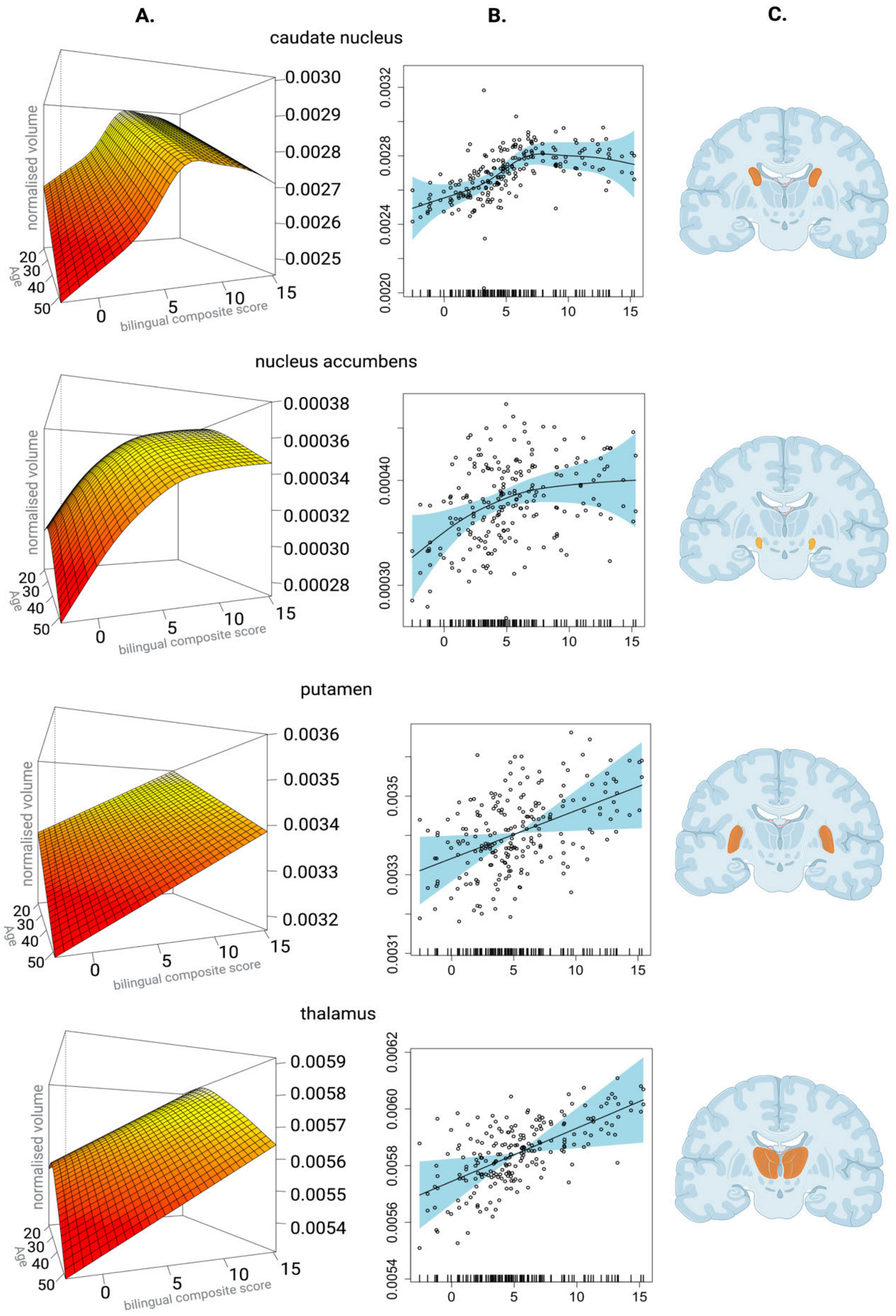


Figure 3. Effects of bilingual composite scores on the grey matter volumes of the ROIs.

(A) 3D plots illustrating the relationship between BCS (x-axis), age (z-axis) and normalised volumes of the regions of interest (rows). **(B)** Effects of the BCS scores (x-axis) and the normalised volumes of the regions of interest. **(C)** Featured location of the regions of interest in the brain.

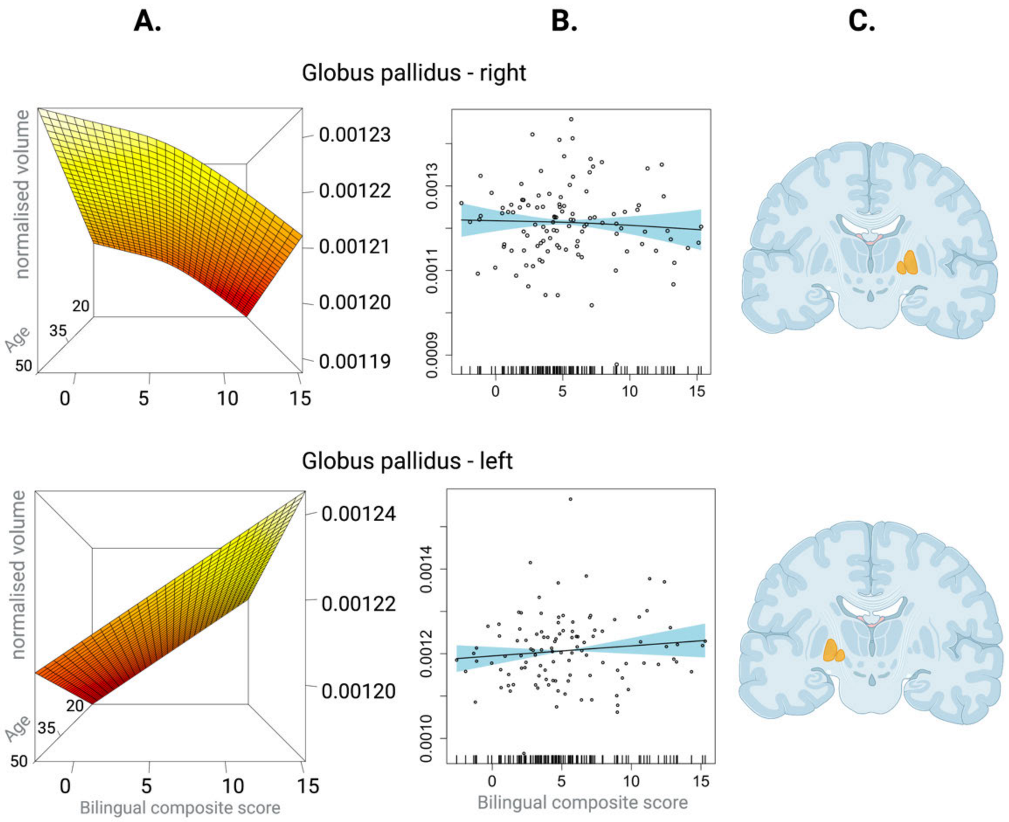


Figure 4. Effects of bilingual composite scores on the grey matter volumes of the globus pallidus.

(A) 3D plots illustrating the relationship between BCS (x-axis), age (z-axis) and normalised volumes of the globus pallidus in the right (upper band) and left hemisphere (lower band). **(B)** Effects of the BCS scores (x-axis) and the normalised volumes of the globus pallidus. **(C)** Featured location of globus pallidus in the brain.

2.3 DISCUSSION

In this paper we show that quantified bilingualism has dynamic effects on the volumetric adaptations of the basal ganglia and the thalamus in a sample of bilinguals with varied bilingual experiences. More specifically, GAMMs analysis revealed volumetric trajectories indicating that the amount of engagement with bilingualism is linked to larger volumes of the caudate and the accumbens in less experienced bilinguals, followed by structural renormalisation in individuals who reached higher levels of bilingual experiences. Furthermore, our results revealed that the amount of bilingual experiences was a positive linear predictor of volumes of bilateral putamen and thalamus. These findings suggest that bilingualism, similarly to other cognitively demanding skills, follows an expansion-renormalisation trajectory that is similar to what has been proposed for experience-based neuroplasticity in general (Lövdén et al., 2013). The observed brain adaptations will be discussed against relevant theories and findings from previous studies below.

The positive relationship of caudal volumes with bilingual experiences that we observed in relatively less experienced bilinguals are consistent with previous studies. Indeed, caudate nucleus has been reported to increase in volume mostly in bilinguals who have not been fully immersed in a bilingual environment (Pliatsikas et al., 2017). Also, the observed decrease of caudal volumes after a certain level of bilingual experiences maps indirectly onto the lack of such findings from studies looking at *experienced* bilinguals: if the volumes of caudate in experienced bilinguals have already renormalised they may not significantly differ to those of monolinguals (Elmer et al., 2014). Overall, this supports the view that caudate subserves cognitive processes needed during the earlier stages of L2 acquisition, which triggers the increases of this structure, such as early lexical control and selection (Abutalebi & Green, 2007). The relatively smaller caudal volumes observed here in more experienced bilinguals signifies optimisation of the neural resources in handling the cognitive demands posed on bilinguals in the early stages of L2 acquisition.

We also observed a volumetric trajectory of the bilateral nucleus accumbens suggesting that this structure increases as a function of growing bilingual experiences and plateau in highly experienced bilinguals, a pattern that partly matches the one for the neighbouring caudate nucleus. This pattern expands on previous findings showing that length of language acquisition predicted contractions in bilateral accumbens, and social language use predicted expansion of the left accumbens (DeLuca et al., 2019). The nucleus accumbens likely subserves the reinforcement of learning strategies (Green & Abutalebi, 2013). Also, larger accumbens volumes have been reported in individuals with more extensive social networks (Ospina et al., 2019). In the context of the current findings, the nucleus accumbens can be responsible for reward in seeking social interactions in the earlier stages of L2 acquisition to encourage bilingual practice. The plateauing pattern reported here might reflect that when bilinguals reach the necessary language use efficiency the intrinsic motivation to seek social interaction in their L2 stabilises. This might be particularly true for participants in the present study who stayed in their home country. In such context, their communicative skills in the L2 do not necessarily determine their social well-being as they have enough chances to build their social interactions using their L1. In turn, such behaviour becomes superfluous, leading to the stabilisation of their neural resources. However, given that the role of accumbens is less well understood in bilingualism, we remain cautious of this interpretation.

Unlike for caudate and accumbens nuclei, the effect of bilingual experiences on the volumes of the neighbouring putamen was linear, which is consistent with previous studies and our predictions. The putamen is assumed to subserve articulatory control in selecting the appropriate motor schemata in speech production (Viñas-Guasch & Wu, 2017). Therefore, we assume that the current results indicate structural changes toward increased efficiency in the production of L2. Larger putamen volumes have been also reported in previous studies. Specifically, bilinguals with longer or more intensive experience had larger putamen volumes than monolinguals (Burgaleta et al., 2016), or their less experienced bilingual counterparts (Berken et al., 2016; DeLuca et al., 2019). However, the laterality of these effects varied, with increases reported in the right (DeLuca et al., 2019), left (Berken et al., 2016), and bilateral putamen (Burgaleta et al., 2016). Part of the differences with respect to the laterality of the observed effects might stem from variability in phonological transparency of languages the bilingual used, which has been shown to play a role in a previous study (Cherodath et al., 2017). Phonological skills in Hindi, a phonologically transparent language, have been predicted by larger volumes of the right putamen, whereas performance on the same task in English, a relatively phonologically non-transparent language, was linked to larger volumes of the bilateral putamen (Cherodath et al., 2017). These results were interpreted as indication that phonological skills in a non-transparent language require support from both hemispheric parts of this structure. However, this is an empirical question which could be answered in studies where bilingual samples are ensembled based on careful consideration of the language pairs involved.

The observed positive correlation of bilateral thalamus volumes with bilingual experiences might reflect the longstanding necessity for language selection among participants in the current sample. Thalamus is extensively connected to the basal ganglia and the medial prefrontal cortex subserving language and domain-general cognitive control (Abutalebi & Green, 2016; de Kloet et al., 2021). Furthermore, emergent views highlight the thalamus' role in shaping mental representations involved in learning and memory (Wolff & Vann, 2019). Accordingly, the present findings may reflect the need for bilinguals to constantly update mental representations. Experienced bilinguals in our study, including professional interpreters and translators, need to permanently monitor extent to which boundaries between concepts are similar across both languages. For example, the English word *chair* can refer to conceptually very distinct objects, such as *a desk chair, an armchair* or *a deck chair*. In contrast, the Czech translation of *chair* (*židle*) cannot refer to *a deck chair*, as this object falls within a category of *beds*. Thus, a translator needs to constantly be aware of the fact that conceptual distinctions are mapped onto words in each language in very different ways (Jost et al., 2018; Neumann et al., 2018).

In accordance to some recent findings (DeLuca et al., 2019), we did not observe any effects of bilingualism on the volumes of globus pallidus, which has been shown to expand in experienced bilinguals in other studies (Burgaleta et al., 2016; Pliatsikas et al., 2017). A possible explanation relates to the fact that participants in our study were predominantly Czech natives who lived in Czechia. Globus pallidus has been reported as sensitive to reward-signals (Münte et al., 2017), including reinforcement of behaviour leading to cultural accommodation (Chen et al., 2015; Jie, 2018). In this view, the absence of adaptations of globus pallidus volumes observed here may reflect the lack of need for acculturation expected in participants living in their home country. In contrast, the study that reported increases of globus pallidus (Pliatsikas et al., 2017) included a largely migrant population, with likely higher demands exerted not only on linguistic but also cultural assimilation. However, further research is necessary to tease apart the role of language, cultural acquisition and code-switching on brain structure.

We now turn to the interpretation of the observed patterns with respect to theoretical time course of the bilingualism-induced brain adaptations. Notably, the trajectories of subcortical structural changes observed here appear to be in accordance with the predictions by the DRM (Pliatsikas, 2020). Specifically, the trajectory of caudate adaptations indicates that caudate undergoes structural changes first. The pronounced expansion-renormalisation trajectory of caudal volumes in relation to bilingual experiences can be a sign of an onset of adaptations early in the process of language acquisition. Namely, for a structure to renormalise, it should be provided with sufficient time and training in the given skill to do so. In this view, the caudate have renormalised because it was provided enough opportunity to finetune its architecture as it was intensely relied on from the beginning of bilingual language use.

We observed a similar pattern with respect to volumes of bilateral accumbens, the volumes of which were shown to increase as a function of growing bilingual experiences, and to plateau, but not decrease, in highly experienced bilinguals. Also as predicted by the DRM, the observed volumetric increases the in putamen and the thalamus started later and after some amount of bilingual experience and continued to increase even in the highly experienced bilinguals but without any evidence of plateauing or even renormalising, which may still be the case in bilinguals of more extended experience that were not part of our sample. The observed patterns of grey volume changes and the hypothesised time-course of the adaptations are schematically illustrated in Figure 5. Although these interpretations are in line with our a-priori predictions based on an evidence-based model, we note that further research with longitudinal design is necessary to provide more evidence on the time-course of subcortical adaptations.

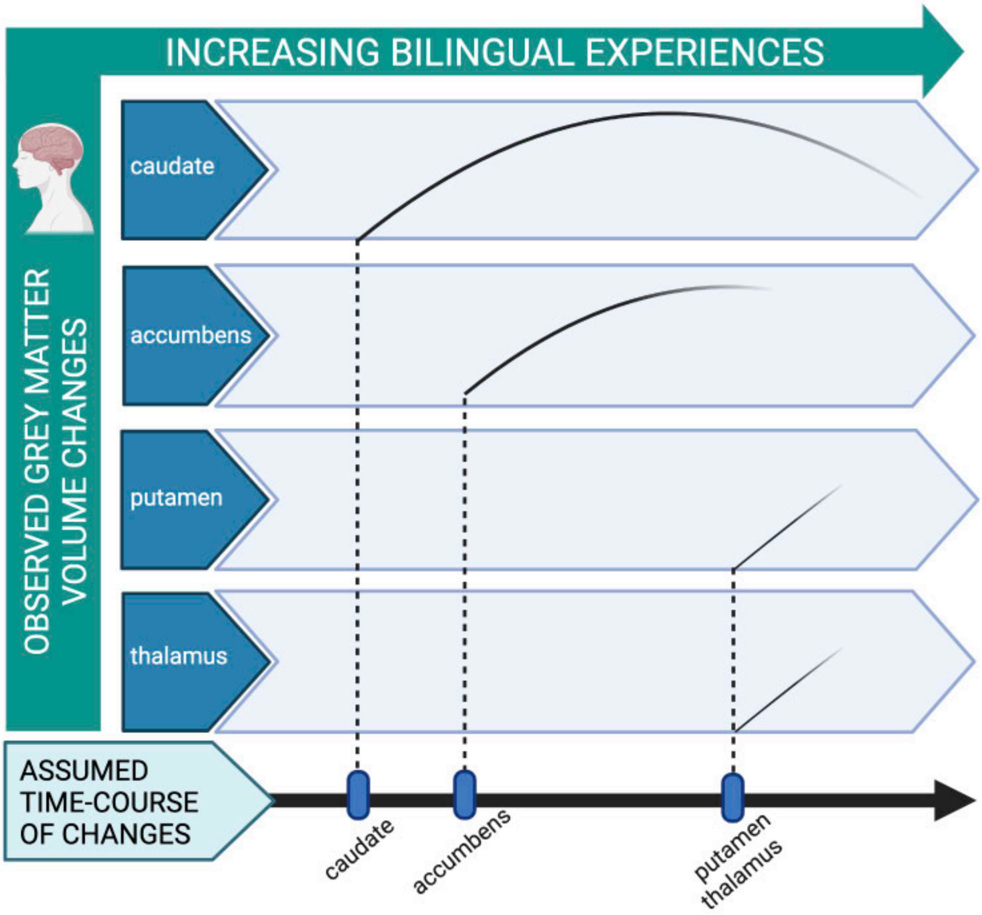


Figure 5. Schematic overview of the observed volumetric grey matter patterns for each of the regions of interest.

The level of renormalisation suggests the time-course of the onset of the brain adaptations (depicted bellow). Regions for which renormalisation of volumes in highly experienced bilinguals was observed (i.e., caudate and accumbens) had likely earlier onset of structural adaptation.

The volumetric patterns observed here (especially those in the caudate and the accumbens) align with the general principles of experience-dependent neuroplasticity. Specifically, these patterns are consistent with the expansion-renormalisation trajectory of experience-dependent brain changes induced by cognitively demanding experiences. For example, Wenger et al. (2017) reported grey matter expansion in motor cortices during the first weeks of motor learning and partial renormalisation following continued practice and increasing task proficiency. If viewed through this lens, existing studies on bilingualism-induced neuroplasticity that focused on the amount of various bilingual experiences also point in the direction that bilingualism induces structural increases that are followed by renormalisation as bilingual language use continues. The caudate and the accumbens both expanded and contracted in bilinguals, dependent on the amount of bilingual experiences (DeLuca et al., 2019). These bidirectional volumetric effects were suggested to reflect both adaptations to newly emerged cognitive demands and the subsequent optimisation of the language control network.

The interpretation that our findings reveal an expansion-renormalisation pattern is further supported by recent study showing that quantified bilingual experiences predicted concentrations of myo-Inositol (INS), a metabolic marker of structural brain adaptations, in a cluster covering the caudate nucleus and the putamen (Pliatsikas, 2021). This finding was interpreted as indirect evidence of renormalisation of these structures on the microstructural level. Although the link between metabolic and the macrostructural brain changes remains poorly understood (Colzato & Hommel, 2021), this evidence complements our current findings from a different sample, and therefore it constitutes a promising step forward in understanding the holistic orchestration of brain adaptations in bilinguals. Overall, the current findings corroborate the view that experiences are central to bilingualism-dependent brain adaptations and extend them to modelled non-linear effects as revealed by GAMMs. Therefore, our results provide firm support for theoretical suggestions that bilingualism encompasses a dynamic set of experiences that pose variable demands on brain structure (Pliatsikas, 2020).

Findings from this study should be appreciated within the context of certain limitations. Although we maintain that our approach of treating bilingualism as a continuum of experiences constitutes a step in the right direction regarding the revelation of dynamic effects of bilingualism on the brain, we do acknowledges that such an approach is relatively novel within the field of bilingualism where a between-group design has been used predominantly. This restricts the comparability of our results to those from previous studies. We also acknowledge that our understanding of the relative contribution of concrete individual bilingual experiences (i.e., code-switching frequency, onset of language acquisition, multicultural identities etc.) on the brain structures is still limited when composite scores like ours are used. A possible way forward in future studies is to combine the use of composite scores of bilingual experiences alongside other continuous measures of individual bilingual experiences and compare the results against each other. Such an approach would make it possible to establish which bilingual experiences or their combined effects have the most prominent effects on the brain structure. Also, the results demonstrated here use a measure of bilingual experiences at the time of data collection. Although such an approach remains valid as a level of current experience is indicative of the time necessary to reach that particular level of experience, individual differences and learning circumstances might compromise the results. A longitudinal study encompassing several measurements with a controlled training paradigm would advance our understanding of the structural adaptation processes brought about by bilingualism over specific periods of time.

In conclusion, this is the first study to prove that bilingualism, a cognitively demanding and complex skill, can trigger non-linear adaptations on the brain structure, expressed as initial expansion of brain volumes with limited bilingual experiences followed by renormalisation of some structures at higher levels of experience, indicating increased efficiency. Therefore, the data support the dynamic view of bilingualism-induced neuroplasticity proposed by Dynamic Restructuring Model (Pliatsikas, 2020), which posits that the intensity of bilingual experiences predicts dynamic patterns of structural adaptations. Our approach also addressed inconsistent results in terms of location and direction of structural brain changes brought about by bilingualism reported in previous studies, which adopted assumptions of linearity of these effects. Thus, our findings constitute an intriguing methodological step toward a unifying explanation for previous work on bilingualism-induced neuroplasticity. On a broader level, the data also support the expansion-renormalisation model, which explains general principles of experience-dependent neuroplasticity (Wenger et al., 2017). Therefore, the current study puts bilingualism forward as a valuable candidate for studies investigating mechanisms of neural adaptations brought about by demanding, life-long experiences.

2.4 METHODS

2.4.1 PARTICIPANTS

Data were acquired from native or native-like speakers of Czech (n = 114; 43 males; 71 females; mean age = 32). All participants had upper intermediate to high command of English as measured by LexTale test for advanced learners of English (Lemhöfer & Broersma, 2012). While keeping our sample consistent in terms of high English proficiency, participants were sampled among bilingual groups with assumed variation in their relevant bilingual experiences. These included bilinguals with a relative short-term bilingual engagement, bilinguals who spent part of their lives abroad, or translators and interpreters. Hereby, we ensured to cover a wide range of relevant bilingual experiences such as onset of language acquisition, intensity of language contact, proportionality of language use, and practices of mixing of both languages. All participants were right-handed, with normal or corrected-to-normal vision and without history of neurological or language disorders. All participants reported holding a university degree or being students enrolled in a university programme. This information was collected using the LSBQ (see *Materials* below). All participants were living in the Czech Republic at the time of testing and reported not to had visited any foreign speaking country two weeks prior testing. To minimize any effects caused by differences in typological proximity between the L1 and English (González Alonso et al., 2020), all participants were native speakers of a Slavic language, with the following languages represented: Czech (n = 106), Russian (n = 4), Macedonian, Polish, Serbian, and Slovak (for each n = 1). The non-native Czech speakers were all court interpreters/translators in language combination Czech-English, which means they needed to fulfil the conditions stipulated by the Czech legal Act on Experts and Interpreters no. 36/1967 Coll. (Czechia, 1967) including, native or native-like knowledge of Czech.

Five participants (native speakers of Czech) did not finish the whole scanning procedure, and their data were excluded from this study. The sample submitted for analyses consisted of 109 participants [39 males; 70 females; mean age (SD) = 32 (7.71); age range 18-53; mean LSBQ composite score (SD): 5.43 (3.96)].

All participants provided written consent prior the data collection. The study received a favourable opinion for conduct by the Ethics Committee of Masaryk University.

2.4.2 MATERIALS

2.4.2.1 LANGUAGE AND SOCIAL BACKGROUND QUESTIONNAIRE

To assess the participants' level of bilingual language engagement, participants completed a Czech version of *The Language and Social Background Questionnaire* (Anderson et al., 2018c). This questionnaire gathers information about the demographics, code-switching practices, language background, history, language use and proficiency. Answers to the questions marked on five-point or ten-point Likert scales are entered into an overall factor score calculator (Anderson, et al., 2018c), which creates LSBQ composite score of bilingual experiences, therefore assessing bilingualism as a continuous variable (Pliatsikas, 2021). The Czech version was translated from

English and back-translated to determine the quality and equivalence of the Czech version with the source version. This questionnaire is attached as *Appendix F*.

2.4.3 MRI DATA ACQUISITION

MRI data were collected at the Central European Institute of Technology (Brno, Czechia) on a 3T Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil.

We carried out high-resolution anatomical scans for registration and structural analysis (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 acquisition of anatomical scans took about 10 minutes.

2.4.4 DATA ANALYSIS

2.4.4.1 MRI DATA PREPROCESSING

We used the FSL_anat software pipeline (Jenkinson et al., 2012) to preprocess T1-weighted images. The subcortical structures were extracted using the FIRST software pipeline (Patenaude et al., 2011). The following structures were automatically segmented for both hemispheres separately and were visually inspected for quality of extractions: accumbens, caudate nuclei, globus pallidus, putamen, and thalamus. To account for the impact of head size on the volume of subcortical regions, we divided the volumes of each region by the whole-brain volume. These proportional volumes were then submitted to the statistical analysis. The mean proportional volumes of the regions of interest are illustrated in the Table 2.

Table 2. Mean and SDs of the proportional volumes of ROIs

	Mean proportional volume (SD)	
	Left	**Right**
accumbens	0.379 (0.071)	0.317 (0.071)
caudate	2.661 (0.226)	2.71 (0.281)
globus pallidus	1.213 (0.09)	1.208 (0.082)
putamen	3.408 (0.243)	3.348 (0.252)
thalamus	5.844 (0.34)	5.712 (0.327)

Note: all values multiplied by 1000 for the purposes of illustration

2.4.4.2 STATISTICAL DATA ANALYSIS

Data were analysed in R (R Core Team, 2019) with generalised additive mixed models (GAMMs) using the gam() function of the mgcv package (Wood, 2011a). The non-linear regression splines in GAMMs are computed as the sum of simpler non-linear functions for each of the fitted variables. However, the non-linear splines are only included when there is enough evidence in the data for a curved function, because the wiggliness penalizes the estimated model fit. GAMMs compute the estimated degrees of freedom (edf), which indicate whether the predictor is in a non-linear (edf>1) or a linear relationship (edf=1) with the dependent variable. We ran a series of GAMMs for volumes of each subcortical region.

In a first-level model, we fitted the regression splines for the main effect of bilingual experiences using BCS along with the main effect of Age, and Participant and Gender as random effects. The smooth term of Age was included to account for previously observed non-linear age-related developmental changes (Pliatsikas, Meteyard, et al., 2020). To estimate the effects of both main effects and interactions, we applied an analytical procedure in line with the "vibration of effects" approach (Patel et al., 2015). We included BCS x Hemisphere interaction, where Hemisphere was an ordered factor with two levels (left and right). We examined effects of this interaction to account for previously reported cases when the observed effects of BCS on brain volumes were lateralized (DeLuca et al., 2019). 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 BCS were considered reliable only if they emerged significant in both relevant versions of the model with different reference levels.

In the second-level model, for the structure where interaction emerged as significant, we split the data for the left and right hemisphere and ran two models for each hemisphere with BCS and Age as main effects and Gender as random effect. For those regions where the BCS x Hemisphere interaction did not emerge as significant, we analysed the main effects of BCS and Hemisphere using data collapsed across hemispheres. These models further included Age as main effect and Gender and Participant as random effects.

2.4.4.3 THE ASSESSMENT OF MODELS FITS

To assess the model fits of all the final models, we used the gam.check() function of the R package *mgcv* (Wood, 2017b). All the final models converged (convergence range: 7-10 iterations). The number of functions which gave rise to the regression splines exceeded in all cases the estimated degrees of freedom. For all continuous variables submitted to the analyses, there were no significant patterns in residuals as evaluated by the p-value above the 0.05 significance threshold. Also, the k-index was in all cases above 1 which supports the view that there were no missed patterns in residuals in our models (Wood, 2017). The results of the model assessment analyses can be found in *Appendix B*.

SUSTAINED BILINGUAL EXPERIENCES CAUSE NONLINEAR STRUCTURAL BRAIN ADAPTATIONS: INSIGHTS FROM INTERPRETERS AND TRANSLATORS.

ABSTRACT

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 non-professional but equally proficient bilingual controls. We used Bayesian Generalised Additive Mixed Models to model effects of quantified general bilingual experiences on the structures of interest. Between-group comparisons revealed larger volumes for both structures in interpreters and translators compared to controls. 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 highest 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 non-professional 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 both the quantity and quality of bilingual experiences. These findings shed new light on the ways in which extremely demanding bilingual experiences affect neuroplasticity in bilinguals.

3.1 INTRODUCTION

One of the most exciting discoveries in the field of bilingualism is that acquisition and use of a second language (L2) can trigger structural adaptations of our brain (Green & Kroll, 2019). These adaptations are believed to result from the constant need of bilinguals to choose between two competing linguistic alternatives and switch between them (Li et al., 2017). Such an unrelenting mental conflict is suggested to pose new demands for cognitive processes necessary for language control and cognitive control in general (Kroll et al., 2012). As a result, the brain adapts structurally to meet the emergent demands. Indeed, there is growing evidence that bilingualism, similarly to other demanding experiences, induces structural brain adaptions that are dynamic and dependent on the intensity and amount of the relevant experiences (DeLuca et al., 2019; Pliatsikas, 2020). However, it is still poorly understood how the brain changes in reaction to sustained and exceptionally challenging bilingual experiences. To fully understand the transformative power of bilingualism on the brain, a better understanding is needed of the effects of all types of bilingual experiences, including the highly challenging ones. Such findings could not only adequately inform theoretical frameworks describing effects of bilingualism on the brain structure, but also broaden our understanding of brain adaptations induced by extremely challenging skill acquisition in general. For this reason, we here investigate the structural brain alterations in bilinguals with exceptional, long-standing, and sustained engagement with both languages: 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 *non-professonial bilinguals*) in their everyday lives. However, professional bilingual practices likely engage these processes more intensively (García et al., 2020). Moreover, it has been assumed that despite the above-mentioned similarities between translating and interpreting, these two activities too require different levels of neurocognitive processing (Garcia, 2014; Santilli et al., 2019). Compared to translating, simultaneous interpreting (SI) is conditional on mastering specific skills such as simultaneous processing, rapid language switching under time-pressure, and control for the correct articulation. This is because simultaneous interpreters (SIs) must listen to and comprehend messages in one language while concurrently converting them and produce them, usually orally, in another language in real time. This has led to claims that translating poses lower demands on cognitive processes than interpreting (M. Becker et al., 2016), which in turn would lead to different effects in brain structure (Hervais-Adelman & Babcock, 2020).

Higher cognitive demands are not only linked to professional bilingual practices, but also to handling two languages in general (Green & Kroll, 2019). In fact, all bilinguals need to employ cognitive control processes to select the lexical, phonological and grammatical repertoires appropriate for the given communicative circumstances, and adapt their strategies when the communicative environment changes (Beatty-Martínez et al., 2019). The orchestration of such a huge variety of tasks also requires a comprehensive neurobiological basis to deal with them.

Two influential models have been proposed concerning the neurobiological basis of bilingual language control: the *Adaptive Control Hypothesis* (ACH; Green & Abutalebi, 2013) and the *Conditional Routing Model* (CRM; Stocco et al., 2014). Both models highlight the same key set of nuclei in the management of the cognitive control involved in dealing with the use of two or more languages: the basal ganglia. Relevant to the current study, two regions within the basal ganglia identified to be important for both simultaneous interpreting (Elmer, 2016; Hervais-Adelman et al., 2015b) and translating (e.g. Lehtonen et al., 2005; Price et al., 1999) are the caudate nucleus and the putamen.. Indeed, the more recent *Neurocognitive model of simultaneous interpreting* (NMSI; Hervais-Adelman & Babcock, 2020) posits two functionally distinct control pathways centred upon these two structures. Specifically, the caudate nucleus is hypothesised to subserve cognitive 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 & Babcock, 2020).

The distinction of the caudate's and putamen's functionalities with respect to processes involved in interpreting as proposed by the NMSI has been informed by a recent fMRI study (Hervais-Adelman et al. 2015b). The study examined the brain activation of caudate and putamen during interpreting and during a monolingual simultaneous repeating (or shadowing) task. The subject group consisted of multilingual participants and included also novice interpreters. Brain activity was compared during two experimental conditions. First, during an interpreting task, participants were listening to a stream of speech in their weaker language while producing its translation in the dominant one. Second, during the shadowing task, participants simultaneously listened to and repeated sentences in the same language. The between-condition comparison revealed increased activity in caudate nucleus in the bilingual interpreting condition compared to the shadowing condition, but no significant effects in the putamen. Furthermore, the authors investigated differences in brain activity triggered by the level of simultaneity in both conditions, 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 in cases of long overlap between the input and output speech than in the shadowing condition. Simultaneity did not emerge as significant modulatory factor for the activity of caudate. These findings highlight that the two structures do not have the same roles during simultaneous interpreting.

Caudate and putamen have not only been shown to be more activated during language-control tasks, but also to adapt structurally following engagement with two languages (Pliatsikas et al., 2020). This process is called experience-dependent neuroplasticity and refers to the ability of the brain to adapt to the cognitively demanding process of acquiring and mastering a new skill (Lövdén et al., 2013). In case the existing brain structure cannot effectively subserve the emergent demands, the brain adapts its structure accordingly. In the case of caudate and putamen in bilinguals, structural comparisons between various bilingual groups and monolinguals have led to conflicting findings, with both larger and smaller volumes being reported (Berken et al., 2016; Burgaleta et al., 2016; Pliatsikas et al., 2017; Zou et al., 2012). Recent studies suggest that these effects in regional brain volumes can be explained by the nature of bilingual experiences (DeLuca et al., 2019; Hervais-Adelman et al., 2018). In this view, the contradictory observations of the volumes of caudate and putamen can at least partly be reconciled if viewed as results of dynamicity of bilingual experiences and are studied within bilingual groups (DeLuca et al., 2019; Luk & Bialystok, 2013).

Experienced-based approach have been applied in the context of bilingualism in the Dynamic Restructuring Model (DRM; Pliatsikas, 2020). DRM re-examined findings from available studies on bilingualism-induced changes against the backdrop of experience-based neuroplasticity mentioned in the previous paragraph. The evidence came predominantly from studies comparing monolinguals with an array of bilingual populations of various ages, language proficiencies and backgrounds, onsets of language acquisition, and various professional experiences, including studies on simultaneous interpreters. The core hypothesis of the DRM is that individual differences in bilingual language use and level of bilingual experiences induce distinct brain adaptations which follow a so-called expansion-renormalisation trajectory, like many other demanding experiences do (Wenger, Brozzoli, 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.

For these purposes, Pliatsikas (2020) proposed three stages of brain restructuring based on the assumed effects of bilingual practices typical for each of the stages. At the first stage, participants 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 & 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 & 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. The third stage describes the brain adaptations occurring in exceptionally experienced bilinguals. Simultaneous interpreters are expected to be typical representatives of this 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. 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 current authors conducted a study aimed to directly test the predictions of the DRM (Korenar et al., in prep – see Chapter 2). In bilinguals with a rich array of experiences, bilingual experiences were used as predictors of subcortical volumes using Generalised additive mixed models (GAMMs), which can capture potential non-linear effects. The findings suggest that the caudate is the first subcortical structure to renormalise in volume in highly experienced bilinguals, in line with its stated importance in particular in the early stages of bilingualism. By contrast, putamen volumes did not show any signs of renormalisation across the same levels of bilingual experiences. 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 study was not designed to determine whether professional bilingual experiences contributed to the results observed.

In the context of simultaneous interpreting (SI), there are two existing studies which investigated the effects of SI on grey matter, with one of them informing the predictions of the DRM (Elmer et al., 2014). This study compared volumes of grey matter in SIs 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 authors also performed a correlational analysis within the group of SIs to identify the changes in grey matter volume that were related to hours of interpreting training. The correlational analysis revealed that the volumes of bilateral caudate nuclei were negatively correlated with the number of hours of interpreting experience. 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. Moreover, between-group comparisons of grey matter in SIs and non-professional multilinguals revealed that interpreters had smaller grey matter volumes of several regions subserving language control, i.e., the left cingulate, bilateral inferior frontal gyrus, insula, and superior medial gyrus, but not the caudate nucleus. The authors ascribed the absence of a caudal effect to the small sample size (12 interpreters and 12 multilingual controls) and low statistical power (Elmer et al., 2014).

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 right putamen and right caudate 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 non-professional 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. This suggests volumes of both caudate and putamen were reported to be larger in trainee interpreters as they were still in training (Babcock, 2015). In contrast, caudate was reported to be smaller with growing interpreting experiences, which likely suggests renormalisation of this structure in fully trained interpreters whose interpreting skills have been largely consolidated (Elmer et al., 2014).

Increase of volumes of the caudate and the putamen in interpreters in training and decrease in caudate volumes and absence thereof in putamen volumes in fully trained interpreters suggests a dissociation of the timelines of adaptations in these structures in line with predictions posited by DRM. The decrease of caudate volumes suggests that this structure subserves cognitive control processes, which are necessary from the very beginning of simultaneous interpreting. The employment of caudate at the early stages of bilingual experiences as posited by the DRM provides the structure with long enough time window to renormalise as it increasingly becomes more efficient in fully trained interpreters. As for the observed larger caudate volumes in trainee interpreters relative to trainee translators, it is possible that the process of volume increases in the former group was still ongoing. As for the putamen, it likely subserves bilingual-related processes which are employed at later phases of bilingual language use, such as increased articulatory control. According to the DRM, this would mean that the process of expansion-renormalisation of this structure has a later onset, although evidence for renormalisation of putamen volumes in highly experienced bilinguals is currently lacking.

Taken together, existing evidence suggests that the roles of caudate and 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 a,b). An intriguing hypothesis that arises is that structural adaptations might differ among various groups of bilinguals. In this view, distinct trajectories of the putamen and the caudate are to be expected due to the group-specific bilingual demands.

3.1.1 THE CURRENT STUDY

Here 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: non-professional bilinguals, translators and interpreters.

In contrast to previous studies, we here investigate 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 so doing, we embrace the fact that interpreters, albethey extreme bilinguals, 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 the brain structure. We capture the bilingual experiences by a composite score of *the Language Social Background Questionnaire* (LSBQ; Anderson et al., 2018c), which is a continuous measure of bilingual experiences. The LSBQ has been successfully used as predictor of bilingualism-triggered brain adaptations in other studies (Anderson et al., 2018b; Aveledo et al., 2020; DeLuca et al., 2019; Martínez-Horta et al., 2019; Pliatsikas, 2021).

Second, it is worthwhile to investigate the effects of simultaneous interpreting through the lens of available evidence on mechanisms of experience-dependent plasticity. To do so, we follow recommendations from the recent studies which adopted this approach (Korenar et al., in prep.; Pliatsikas, 2021; Pliatsikas et al., 2020). Our design is based on the assumption that experience-based changes can be non-linear. 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 the 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 & Wood, 2012).

We formulate several hypotheses regarding group differences in the volumes of caudate and putamen. Based on DRM predictions and empirical findings, we expect that interpreters will have smaller volumes of both caudate and putamen than non-professional bilinguals and translators. There is no available evidence on the volumetric difference between bilinguals with translators. However, given that translators fall somewhere between bilinguals and interpreters in terms of language use patterns, we expect that their caudate and putamen volumes will also fall somewhere between these two groups.

The DRM also provides a basis for hypotheses for the correlational analysis with bilingual experiences treated as predictor of volumes of caudate and putamen within each group. We expect to observe patterns of expansion-renormalisation of the caudate volumes in all three groups, which may vary in shape and its pronouncement 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, as well as a steeper decrease compared to similarly experienced non-professional bilinguals and translators. The pattern of expansion-renormalisation in the latter groups will be flatter, with milder increases and decreases in translators and still milder effects in non-professional bilinguals.

The putamen has been observed to be larger after interpreting training and to grow with increasing bilingual experiences (Babcock, 2015; Korenar et al., in prep - see Chapter 2.). Moreover, it has been implicated in the inhibition of one of the languages during simultaneity of speech input and output (Hervais-Adelman et al., 2015b), and in control of articulatory programmes (Abutalebi, Rosa, et al., 2013), both processes arguably being of the highest importance for interpreters compared to our other groups. We therefore 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 non-professional bilinguals.

3.2. RESULTS

3.2.1 VOLUMETRIC GROUP DIFFERENCES CONTROLLING FOR AGE

Figure 6 illustrates the results of the analyses of volumetric group differences while taking age into consideration, using GAMs. The results revealed a significant main effect of Group on the caudate volumes ($p = 0.013$) and the putamen volumes ($p = 0.01$). Bilinguals had significantly smaller volumes of the caudate compared to both translators ($p = 0.004$) and interpreters ($p = 0.048$). Furthermore, bilinguals were also found to have significantly smaller putamen volumes than translators ($p = 0.024$) and interpreters ($p = 0.005$). There were no significant differences between translators and interpreters in the caudate volumes ($p = 0.558$), nor in the putamen volumes ($p = 0.412$). Age emerged as a significant predictor for the caudate ($p < 0.001$) with the volumes decreasing with older age. A similar relation did not reach significance for the putamen ($p = 0.088$), but there was a downward non-linear trend.

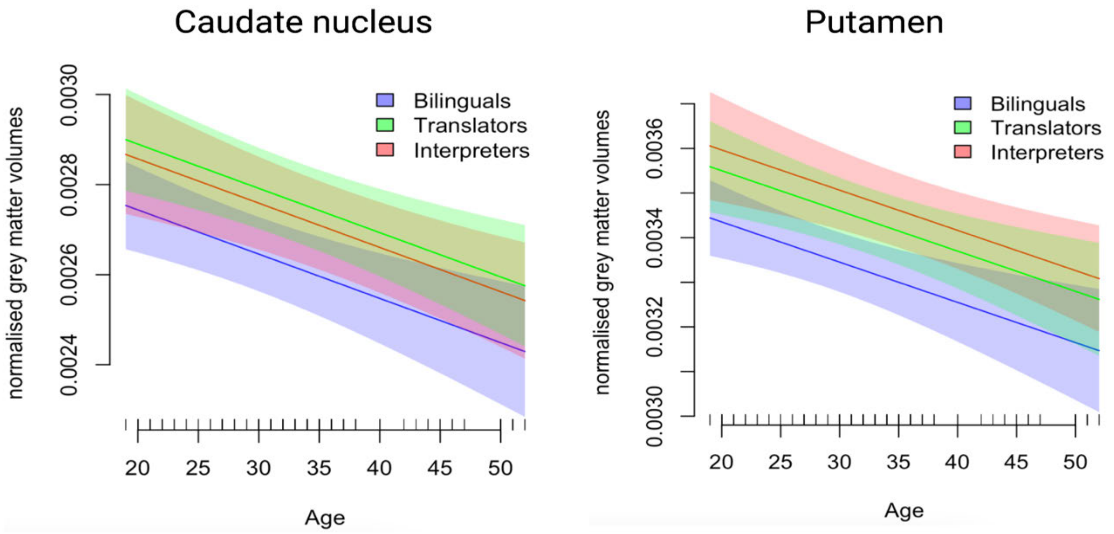


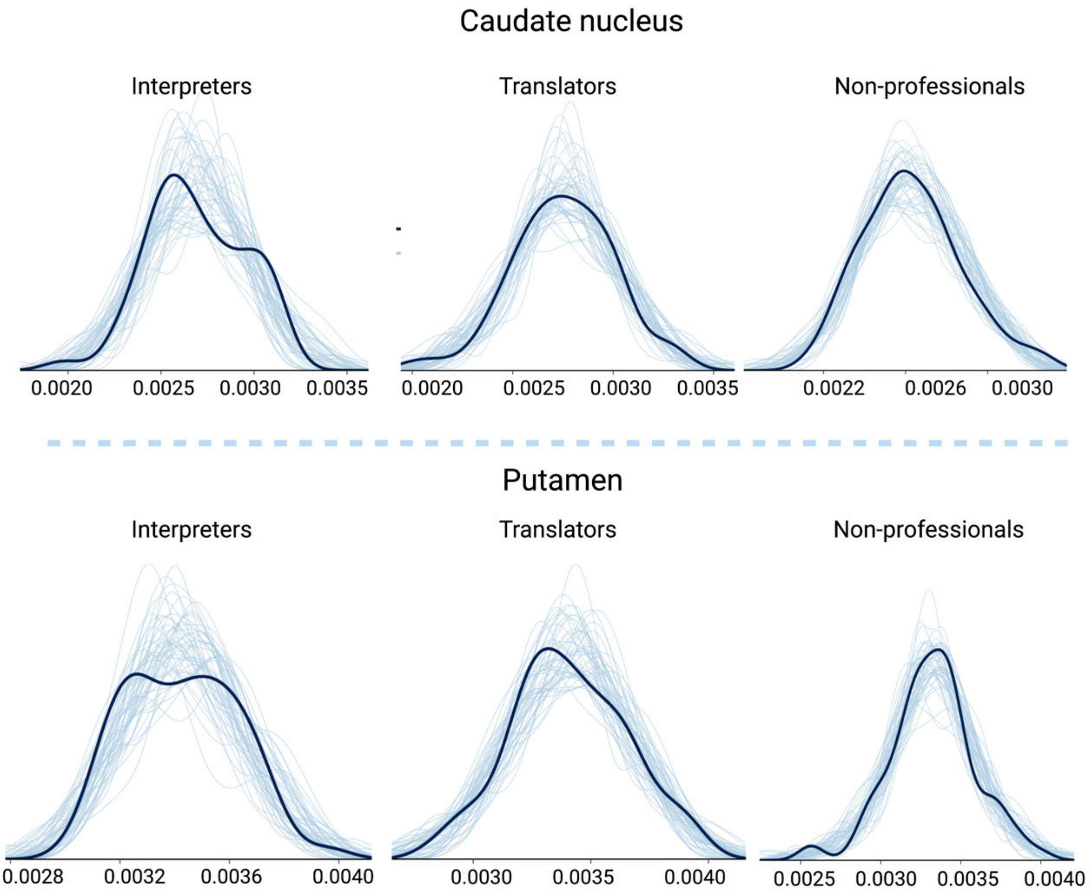
Figure 6. Group differences and the effects of age on the normalised volumes of the ROIs.

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., non-professionals) vs. Translators; Bilinguals vs. Interpreters.

3.2.2 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. To evaluate how well the models fit our data, the predicted values for all iterations are compared to the actual values in Figure 7. The observed data fall into fields of the predicted data distributions, which indicates good model fits.

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 Figure 8. 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. 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.



Caudate nucleus

Interpreters Translators Non-professionals

Putamen

Interpreters Translators Non-professionals

Figure 7. 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)

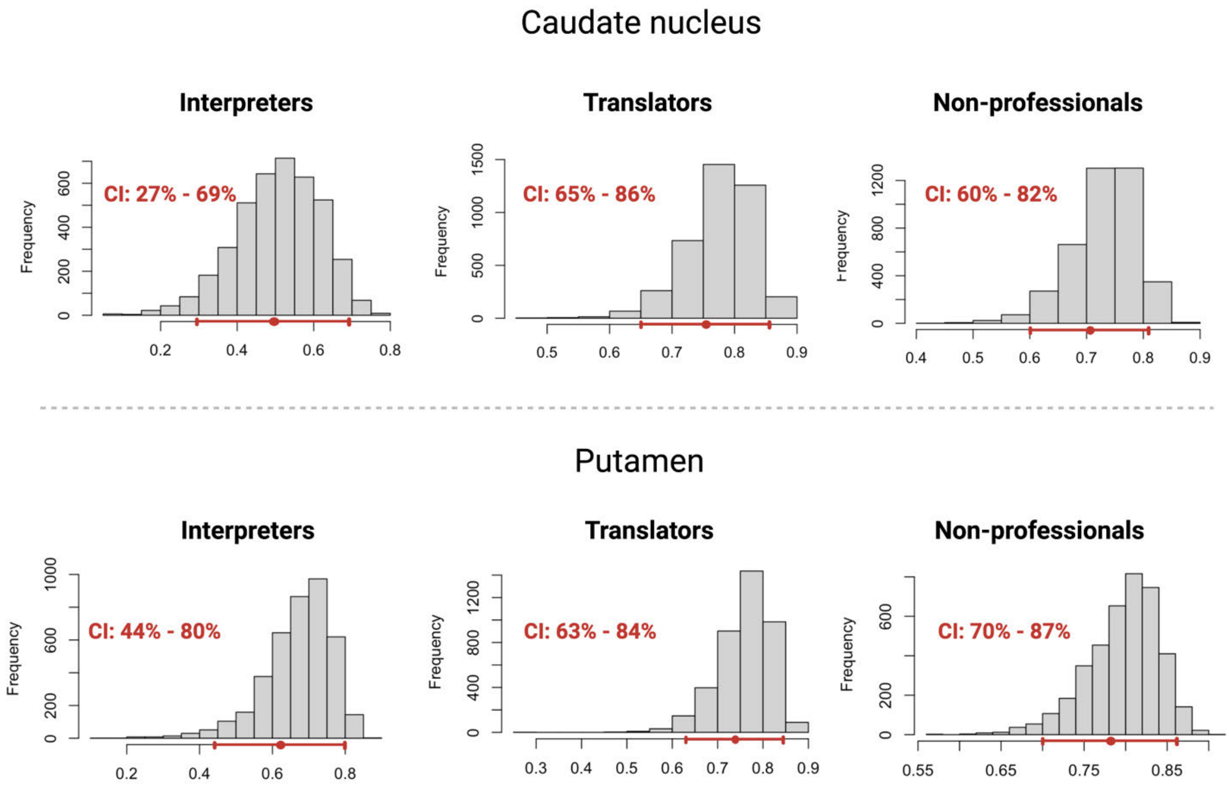


Figure 8. Posterior probability distribution of the R^2 values

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 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)

3.2.3 RESULTS OF BAYESIAN MODELLING

The effects of LSBQ scores for each group on the volumes of each ROI are shown in Figure 9. For interpreters, the degree of bilingual experiences on the volumes of the caudate and putamen in interpreters are estimated to follow an inverted U-curve. Specifically, with increasing levels of bilingual experiences, volumes of both caudate and putamen are estimated increase first, and to decrease after a certain level of bilingual experiences has been reached. Notably, the extent of bilingual experiences after which the renormalisation occurs is higher for putamen than for caudate.

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

The relation of LSBQ scores with ROI volumes in non-professional bilinguals reveal that caudate and putamen are positively and non-linearly predicted by bilingual experiences. The slope depicting the positive effect was steeper for caudate than for putamen.

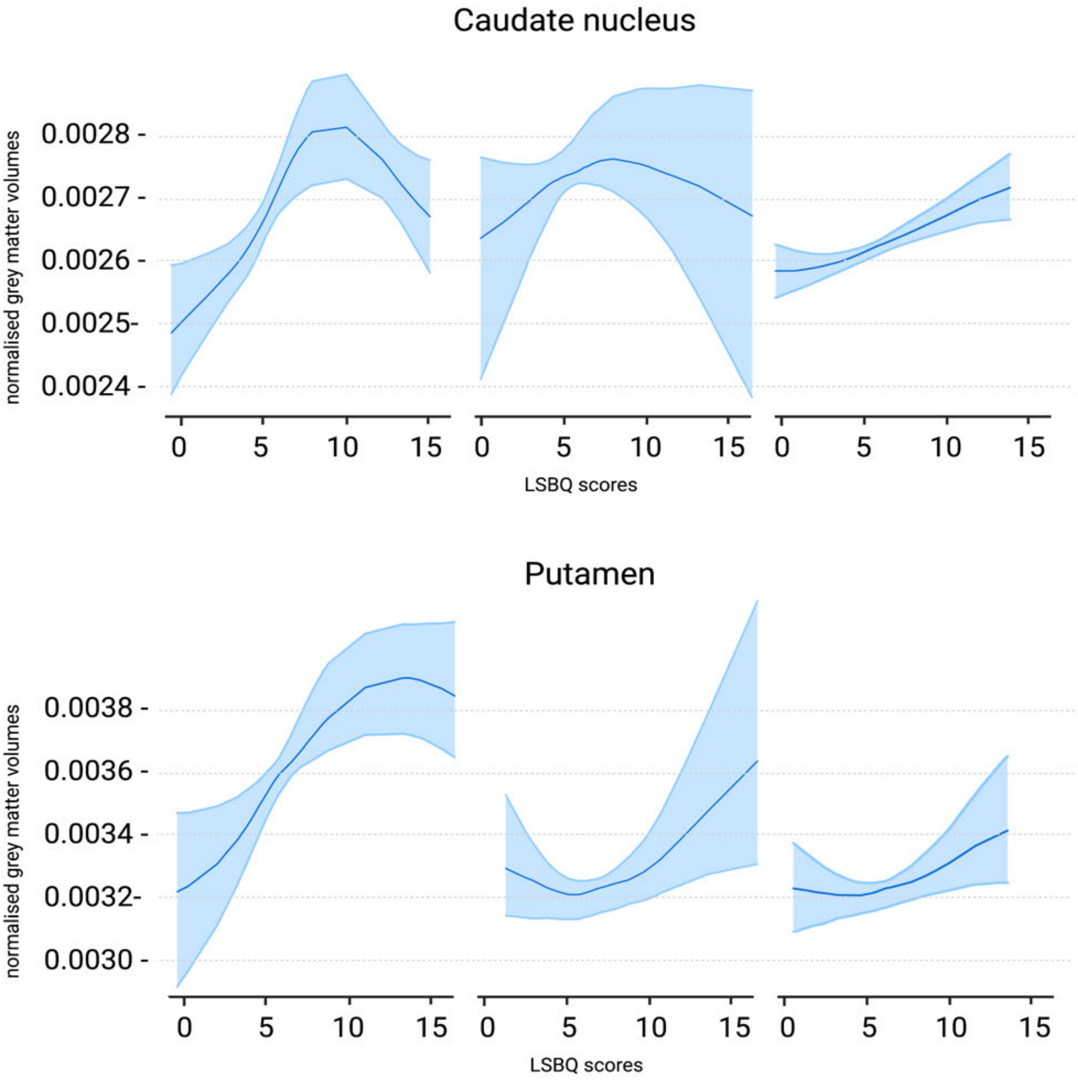


Figure 9. Estimated effects of LSBQ scores on the normalised volumes of ROIs.

Estimated effects of LSBQ (x-axes) scores on the normalised volumes of the caudate nucleus (upper band) and putamen (lower band) in interpreters (left), translators (middle), and non-professional bilinguals (right).

3.3 DISCUSSION

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

Our between-group comparisons revealed that professional bilinguals show larger caudate and putamen volumes than non-professional bilinguals, with no differences observed between translators and interpreters. Furthermore, we observed that bilingual experiences which are common to all bilinguals predict volumetric adaptations of caudate and putamen. Notably, our results revealed that these adaptations follow dynamic trajectories that vary in shape and intensity among the three bilingual groups under study. We will further discuss the importance of these results for broadening our understanding of bilingualism-induced neuroplasticity in the contexts of previous studies and relevant theories.

Our finding of larger caudate and putamen volumes in professionals relative to non-professionals is consistent with the view studies that increased and sustained language control demands can results in larger grey matter volumes (Burgaleta et al., 2016; Pliatsikas et al., 2017). In this view, larger caudate and putamen volumes in interpreters and translators compared to non-professionals would reflect increased demands for control of two languages related to their professions. However, this finding is in contrast with Elmer et al. (2014), who reported that highly experienced interpreters did not have significantly different caudal volumes compared to multilinguals. This discrepancy can be attributed to methodological differences between the two studies, including the segmentation methods of the structural MRI images, different statistical approaches, and the substantially smaller sample in Elmer er al.. Moreover, the samples in both studies likely differed in the range of professional experiences among the subject groups. Also, compared to Elmer et al., the current study kept the language pair constant. In this view, part of the discrepancies could be ascribed to 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.

We did not find support for our hypothesis that interpreters would have larger caudate and putamen volumes than translators. This hypothesis was motivated by Babcock (2015) who revealed that novice interpreters had larger caudate and putamen volumes compared to novice translators after two years of training (Babcock, 2015). Similarly, this discrepancy can stem from differences in data pre-processing and statistical analysis, linguistic proximity, and most importantly, to differences in bilingual experiences of the subjects in both studies. 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 highlighted above by investigating how quantified bilingual experiences affect the putamen's and caudates' volumetric adaptations and their trajectories within each group. The volumetric changes observed in the caudate align with the expansion-renormalisation trajectory. Specifically, in less experienced interpreters, volumes of the caudate were positively related to LSBQ scores, and in highly experienced interpreters, volumes showed a negative correlation with degree bilingual experiences as reflected in LSBQ scores. This finding is line with the only existing study which related volumes of caudate to interpreting experiences and reported that hours of interpreting practices negatively predicted caudate volumes (Elmer et al., 2014). The current result and those of Elmer et al. thus suggest that sustained and extreme involvement in bilingual language control leads to eventual decreases (renormalisation)of caudate volumes.

A similar pattern of expansion-then-renormalisation of the caudate was also partially observed in translators. However, the trajectories in both these groups are distinct in terms of the steepness of observed increases among the less experienced individuals and levels of renormalisation in individuals with exceptionally high experiences. Interestingly, LSBQ scores in translators were highly comparable to those in interpreters. Therefore, the observed variability in the magnitude of the expansion and renormalisation of caudate volumes between these groups cannot be likely ascribed to the quantity of general bilingual experiences alone, but rather to their quantity *and quality* combined. Combining structural data with cognitive tasks in future studies may shed more light on the sources of the qualitative differences observed here.

In contrast, in non-professional bilinguals, growing bilingual experiences emerged as clear positive predictor of caudal volumes. 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 non-professional group investigated here, while highly proficient, 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, the volumetric trajectory of this structure followed the expansion-renormalisation trajectory in interpreters only, which was in line with our predictions. 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). In that vein, we expected interpreters to be the only group in the current study employing processes subserved by putamen with such intensity and frequency, to cause this structure to renormalise.

The caudate and the putamen have been proposed to be at the core of the NMSI which also posits a functional dissociation of these two regions (Hervais-Adelman & Babcock, 2020). Viewed through the lens of the DRM, the intensity with which individuals rely on the functionality of these structures should be mirrored in the way they adapt to the continuous engagement in this activity (Pliatsikas, 2020). With respect to the current study, the putamen renormalised only in interpreters who are likely to rely on its functionality more intensely than other bilinguals (Hervais-Adelman et al., 2015a,b), whereas a trend for caudate renormalisation was also observed in translators. This suggests that the functional dissociation of these structures observed in previous studies was replicated on a structural level in the current study. As such, the current findings provide further evidence for the existing model on the interrelatedness of brain structure and function in extreme bilinguals (Hervais-Adelman & Babcock, 2020).

Taken together, our findings are compatible with and extend the Dynamic Restructuring Model (DRM). The DRM proposes that structural brain adaptations brought about by bilingualism are dynamic but regular, and that the regularity can be revealed if the observed structural effects are viewed as a consequence of the intensity, timing and quality of the bilingual experiences which cause them. The observed renormalisation of the caudate and the putamen in interpreters supports the hypothesis from the DRM that relevant brain structures in interpreters will decrease due to the unprecedented intensity of bilingual language control they face in their jobs. 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 experience 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. The revelation of specific estimates of the volumetric trajectories was enabled by a tool detailing general bilingual experiences on a continuum. To our knowledge the only existing study which used a bilingualism-related continuous predictor of volumetric brain changes in interpreters was that of Elmer and colleagues (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. Conversely, in the current study we were able to compare effects of bilingualism-related experienced in professional and non-professional bilinguals by using a continuous measure of general bilingual experiences which are common to all bilinguals. Even though the LSBQ does not collect any information about professional bilingual practices, splitting the sample according to their professions enabled us to reveal several clear differences in the volumetric trajectories among the three groups under study. Therefore, the LSBQ composite score can be likely used as a valid proxy of professional experiences and its effects on the brain structure.

The relevance and impact of the current study should be evaluated against its possible limitations. First, because 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 LSBQ scores as main predictor on brain volumes could help to distinguish between the neural effects caused by interpreting or translating, and those caused by experiences common to all bilingual groups. 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 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, and has been successful in previous studies (e.g., Haendler et al., 2020; Levshina, 2018; Williams et al., 2018). Overall, this constitutes an important step forward, allowing future studies to leverage the current data set for the creation of highly informative priors.

3.3.1 CONCLUSION

Our study provides new insights into how sustained and exceptionally demanding bilingual experiences affect structural adaptations in caudate and putamen in interpreters, translators and non-professional bilinguals. Our results reveal that general bilingual experiences have dynamic, non-linear effects on the caudate 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.

3.4 METHODS

3.4.1 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.

3.4.2 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 non-professional 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 3.

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 were 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 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 substantial 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).

All participants completed the online version of Lexical Test of Advanced Learners of English (LexTale) (Lemhöfer & 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, 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., 2018). 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., 2018) 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 F*). The translation was created based on the English original. To confirm the quality and equivalence of the Czech translation, an independent researcher back-translated the Czech version to English, which was subsequently examined against the original. 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 = 0.077*]. Post-hoc pairwise Bonferroni did also did not reveal any significant between group differences (I vs. T: *p = 1*; I vs. B: *p = 0.29*; B vs. T: *p = 0.11*) The LSBQ scores for each group can be found in the Table 3.

Table 3. Mean (SD) of group demographics and LSBQ composite scores.

	Non-professional 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 Composite	4.30 (3.96)	6.14 (3.02)	5.87 (4.69)

3.4.2 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 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°. Data acquisition lasted approximately 10 minutes

3.4.3 DATA ANALYSIS

3.4.3.1 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 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 the Table 4.

Table 4. Proportional volumes of the two regions of interest

Mean proportional volume averaged across hemisphere (SD)		
group	**caudate**	**putamen**
bilinguals	2.63(0.23)	3.32(0.25)
interpreters	2.69(0.23)	3.43(0.19)
translators	2.75(0.24)	3.41(0.23)
Total	2.69(0.24)	3.38(0.23)

Note: all values multiplied by 1000 for the purposes of illustration)

3.4.3.2 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 frequentist approach. Data were analysed in R (R Core Team, 2019a) using gam() function of the mgcv package (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.

3.4.3.3 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). 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 Generalised 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" (as per Patel et al., 2015). We fitted six GAMMs with main effect Age and LSBQ x 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 any group and any structure did the LSBQ x Hemisphere interaction emerge as significant in both relevant versions of the models with different reference levels (see *Appendix E* for the results of this procedure). Therefore, we did not fit separate Bayesian models for each hemisphere.

We fitted three Bayesian Generalised Additive Models for both ROIs, one for each of the investigated groups. The response variable were the normalized volumes of caudate and putamen. We treated our main predictor LSBQ as a main effect together with Age and Hemisphere, and subject as 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. The model fits were assessed using of 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).

CHAPTER 4

BILINGUAL SWITCHING PRACTICES HAVE DISTINCT EFFECTS ON THE VOLUMES OF THE CAUDATE NUCLEUS AND THE THALAMUS

ABSTRACT

Bilingualism impacts brain structure, especially in regions involved in language control and processing. However, bilingual experiences are complex and the relation of brain structural changes to key aspects of bilingual language use are thus far poorly understood. Here we used structural MRI and non-linear correlational analysis in Czech-English bilinguals to investigate the effects on brain structure of habitual code-switching practices, a typical bilingual behaviour. We studied the effects of usage frequency of various code-switching types on the volumes of the caudate nucleus and the thalamus, two prominent subcortical structures subserving code-switching. Overall code-switching frequency was measured as well as extent of engagement in various code-switching types. These types were categorised by directionality (L1-L2 or L2-L1) and the level of separation of the two languages. Caudate volumes were positively correlated with overall code-switching frequency, irrespective of code-switching type or directionality, although stronger effects were found for L1-L2 switches within code-switching type correlations. Thalamic volumes were positively correlated with engagement in forms of CS for which the two languages are kept more separate, with stronger effects observed in L2-L1 switches. This pattern of results underscores the theoretical and methodological importance of using detailed measures of bilingual experiences when investigating the sources of bilingualism-induced neuroplasticity.

4.1 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 necessary repertoire of thinking processes and behaviours 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 called into question 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 continuous 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 started to disentangle 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. Part of the seemingly inconsistent findings can 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 & Pylkkänen, 2018; Karalunas et al., 2020; Rey-Mermet et al., 2018). This has rightfully prompted the question whether such measures can really divulge the amount of 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 & Pylkkänen, 2017).

Taken together, to further advance our understanding of how bilingualism gives rise to structural changes, we need to look at an even more elaborate, ecologically valid measure, which details an understudied aspect of bilingual use. Therefore, we focus here on code-switching, 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.

4.1.1 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).

4.1.2 CODE-SWITCHING AND COGNITIVE CONTROL

Why does code-switching come with cognitive costs? Code-switching is marked by 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 appropriate, and inhibition allows for the suppression of one of the languages in rapid succession (Blanco-Elorrieta & Caramazza, 2021).

The processes described above induce increased cognitive demands related to code-switching, which themselves may vary. For example, cognitive costs may differ depending on the *directionality* of the switching. 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 & Witteman, 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 differently require cognitive control processes is the *level of separation* between the two languages within a switch (Green & Wei, 2014b; 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 strongly suppress the unwanted language in the former.

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 ACH, the degree of inhibitory control levels 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 intersentententially. 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 a lesser degree of 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.

Muysken (2013) proposed a typology of intrasententential code-switching types based on the level of separation between two languages[5]. 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 10). 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 10). 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).

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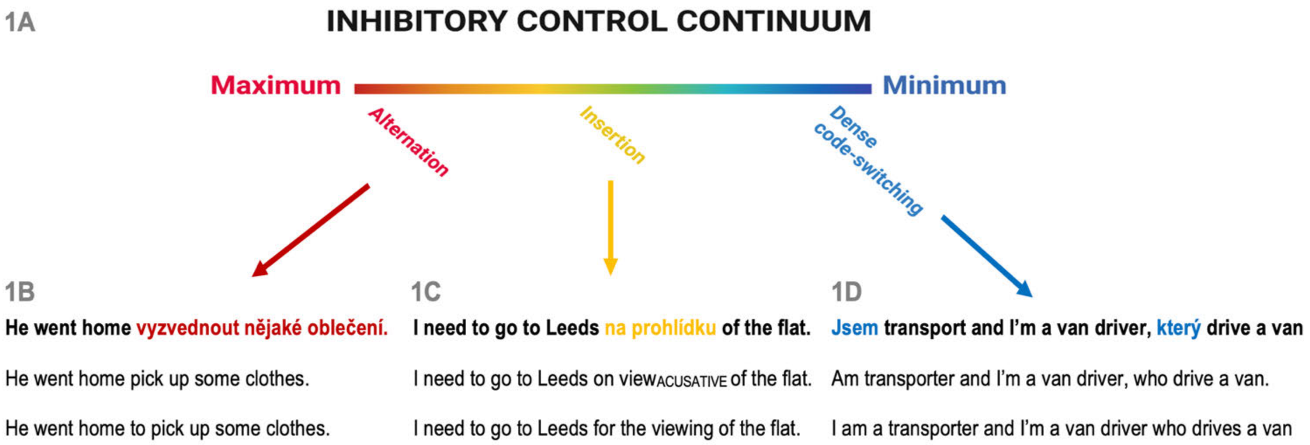
[5] Muysken (2000: 1) calls the intrasentential code-switching "code-mixing".



He went home vyzvednout nějaké oblečení.

He went home pick up some clothes.

He went home to pick up some clothes.

I need to go to Leeds na prohlídku of the flat.

I need to go to Leeds on viewACUSATIVE of the flat.

I need to go to Leeds for the viewing of the flat.

Jsem transport and I'm a van driver, který drive a van

Am transporter and I'm a van driver, who drive a van.

I am a transporter and I'm a van driver who drives a van

Figure 10. Inhibitory control continuum proposed by Treffer-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.

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.

4.1.3 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). 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). Given the prominence of these structures in regulation of cognitive processes during switching, the remainder of this introduction will focus on them in more detail.

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 switching in interpreters (Elmer, 2016; Hervais-Adelman et al., 2015b). 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 (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 caudate nucleus and 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 the vascular damage of the thalamus (Mariën et al., 2005).

The thalamus and 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., caudate), 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 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).

4.1.4 BILINGUALISM-INDUCED STRUCTURAL BRAIN CHANGES IN THE THALAMUS AND THE CAUDATE

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 the continuous measures of bilingual experiences 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). Specifically, 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).

Following up on Deluca et al. (2019), the current authors (Korenar et al., in prep. – see Chapter 2) showed that thalamus volumes related linearly, and caudate volumes 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, caudate volumes 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, which has been put forward in the Dynamic Restructuring Model (DRM, Pliatsikas, 2020). To test the notion of non-linearity, Korenar et al. followed up on previous studies (Pliatsikas, 2021; Pliatsikas, Meteyard, et al., 2020), which utilised Generalised Additive Models (GAMs) for modelling possible non-linear brain adaptations. 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 of 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 isolated, 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.

4.1.5 THE CURRENT STUDY

The current study addresses this call by being the first to examine structural brain adaptations brought about by code-switching practices in Czech-English advanced bilinguals. Here we focus on the caudate and the thalamus, brain regions that have been consistently reported as essential nodes for code-switching (Green & Abutalebi, 2016; Ramezani et al., 2020). We developed a Czech-English version of the Code-switching frequency task (CSFT) (Hofweber et al., 2016), which provides information about participants' overall code-switching frequency, alongside their usage frequency of four code-switching types, which employ inhibitory control processes to different degrees: intersentential code-switching, alternation, insertion and dense code-switching. We will 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 those in the opposite switching direction.

4.2 METHODS

4.2.1 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. All participants had uniform socioeconomic status as indexed by participants' education level as well as that of their parents (Greger, 2012).

4.2.2 MATERIALS

4.2.2.1 CODE-SWITCHING FREQUENCY TASK

To assess the frequency of Czech-English code-switching types that participants engage in, we developed a code-switching frequency task based on Hofweber and colleagues' CSFT (2016). 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[6]. The

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[6] Noteworthy, the CSFT contained also the so-called backflagging stimuli. Backflagging is a subtype of alternation, which was proposed as an additional code-switching type proposed by Muysken in his later work (Muysken, 2013). We did not include this code-switching type into our analysis because of the lack of any existing studies linking backflagging use to executive functions or language processing. Furthermore, the task also contained nine Czech monolingual sentences and nine English monolingual sentences.

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 C*.

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 slýchám neustále" (= I am used to encounter similar sentence all the time) and "Podobné věty nikdy neslýchám" (= I never encounter similar sentences) for the extremes and "Podobné věty tu a tam slýchávám" (= I am used to encounter 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 5 for the frequency of all code-switching types collapsed into average scores. The frequencies of individual code-switching types in different directions are illustrated in Figure 11 and their descriptive statistics can be found in Table 6.

Table 5. 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

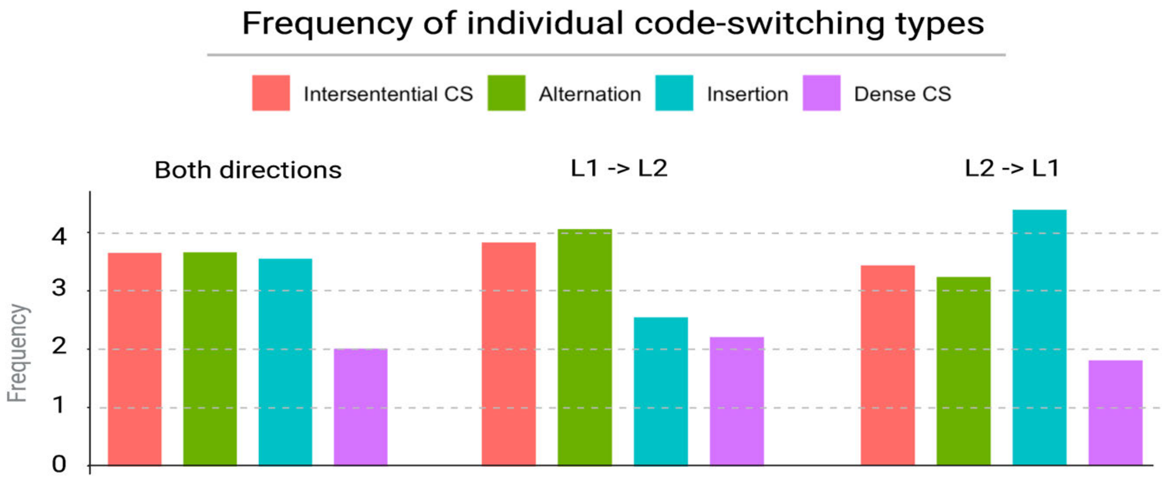

Figure 11. Frequency of individual code-switching types.

Frequencies (y-axis; scale: 0-7) of individual code-switching types (x-axes) in both directions (left column), in L1 –> L2 direction (middle column), and in L2->L1 direction (right column).

Table 6. 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.

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

4.2.3 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.

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

4.2.5 STATISTICAL ANALYSIS

4.2.5.1 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, 2011b) in the statistical software R in RStudio Version 1.4.1106 (R Core Team, 2019b). 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 "wiggliness" comes with a penalty to the overall model fit (Wood, 2011b). 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).

Separate GAMMs were run for normalised thalamus and caudate volumes (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 and were not added to the investigated 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, iv) and the dense-code switching.

The third set of analyses focused on the effects of directionality of each code-switching type on thalamus and caudate volumes. 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.

4.3 RESULTS

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

4.3.1 OVERALL CODE-SWITCHING FREQUENCY

As shown in Table 7 and illustrated in Figure 12, the overall code-switching frequency emerged as a highly significant positive predictor of the volumes of caudate nuclei, but not of the thalamus volumes.

4.3.2 OVERALL CODE-SWITCHING FREQUENCY – SPLIT BY DIRECTIONALITY

Results from this analysis are illustrated in Table 7 and Figure 12. Code-switching frequency in both directions emerged as a significant positive predictor of the caudate volumes, 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.

Table 7. The effects of overall code-switching frequencies on the grey matter volumes of caudate nucleus and thalamus.

	Caudate	**Thalamus**
Overall code-switching frequency	**<0.001*****	0.114
Overall code-switching frequency (L1 to L2)	**0.001****	0.140
Overall code-switching frequency (L2 to L1)	**<0.001*****	0.083

Note: ***: p < 0.001; **: p < 0.01; *: p < 0.05

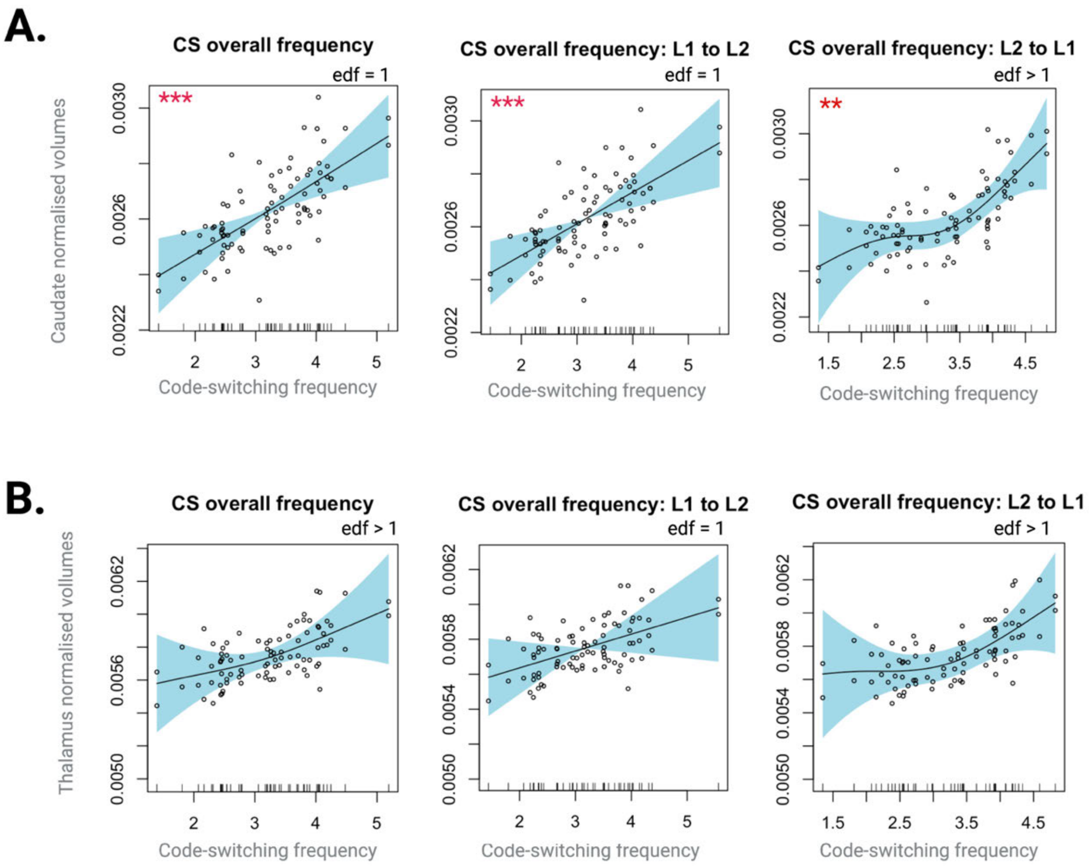

Figure 12. Overall code-switching frequencies and their effects on caudal and thalamic volumes.

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 (A.) and thalamus (B.) volumes. 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)

4.3.2.1 FREQUENCY OF INDIVIDUAL CODE-SWITCHING TYPES AND THEIR EFFECTS ON CAUDATE AND THALAMUS

Results from this analysis are illustrated in Table 8 and Figure 13. 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.

Table 8. The effects of frequencies of code-switching types irrespective of direction on grey matter volumes of the caudate nucleus and thalamus.

Code-switching type	**Caudate**	**Thalamus**
Intersentential CS	**<0.001*** **	**0.002** **
Alternation	**<0.001*** **	**0.038***
Insertion	**0.033***	0.224
Dense CS	0.060	0.099

Note: ***: p < 0.001; **: p < 0.01; *: p < 0.05

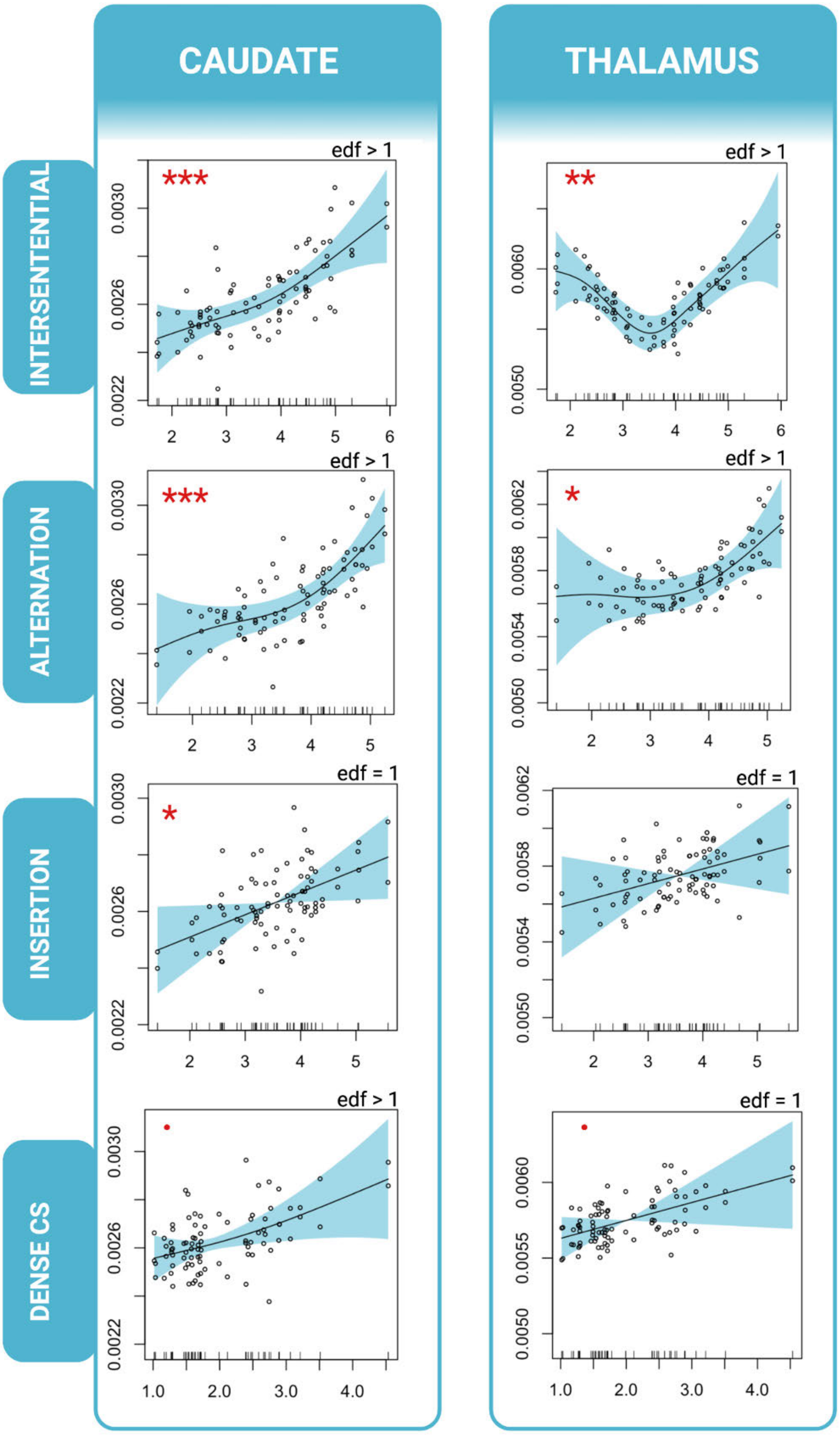

Figure 13 Usage frequencies of individual CS types and their effects on caudal and thalamic volumes.

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 and thalamus (columns). The significance of the effects is marked in red (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; •: $p < 0.1$). Edf = estimated degrees of freedom (edf = 1: linear slope; edf > 1: non-linear slope)

4.3.2.2 FREQUENCY OF INDIVIDUAL CODE-SWITCHING TYPES AND THEIR EFFECTS ON CAUDATE AND THALAMUS – SPLIT BY DIRECTIONALITY

Results from these analyses are shown in Table 9 and in Figure 14. With respect to the L1 to L2 direction, engagements in all code-switching types were revealed as significant predictors of the caudate nucleus volumes. Intersentential code-switching frequency emerged as the only significant non-linear predictor of thalamus volumes, 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 caudate volumes, 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 thalamus 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 thalamus volumes with the right-sided maximum larger than the left maximum, suggesting an overall positive relation

Table 9. The effects of frequencies of code-switching types in both directions on grey matter volumes of the caudate nucleus and thalamus.

Direction	Code-switching type	Caudate	Thalamus
Czech (L1) to English (L2)	Intersentential CS	<0.001***	0.017*
	Alternation	0.014*	0.323
	Insertion	0.022*	0.159
	Dense CS	0.036*	0.120
English (L2) to Czech (L1)	Intersentential CS	<0.001***	0.029*
	Alternation	<0.001***	0.016*
	Insertion	0.165	0.605
	Dense CS	0.077	0.129

Note: ***: p < 0.001; **: p < 0.01; *: p < 0.05

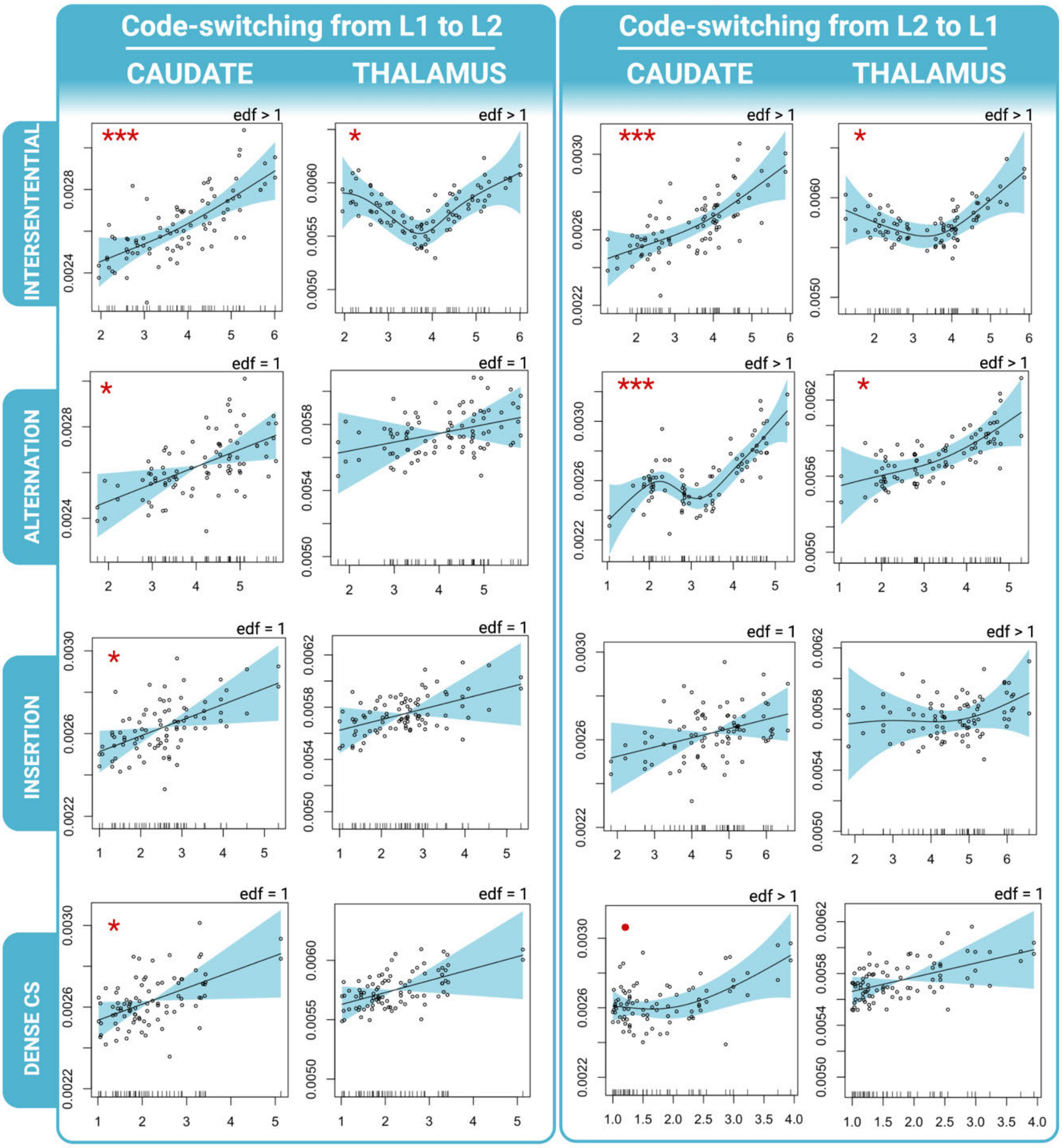

Figure 14. Usage frequencies of individual CS types split by directionality and their effects on caudal and thalamic volumes.

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 caudate and thalamus (column). The significance of the effects is marked in red (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; •: $p < 0.1$). Edf = estimated degrees of freedom (edf = 1: linear slope; edf > 1: non-linear slope)

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 caudate volume. Furthermore, frequent use of code-switching types in which the two languages are more separated consistently predicted larger volumes in both caudate and 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.

4.4.1 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., 2021a). 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 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 should also be involved in all types of code-switching. The positive relationships between caudate volumes 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. 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 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.

4.4.2 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 caudate 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. Caudate volumes 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 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 is involved in both the monitoring and selection of language systems and reactive inhibition. This view aligns with 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 caudate structural adaptations might indeed be sensitive to the modulations of cognitive control processes stemming from the degree of language separation. The caudate expansion 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 proposes 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, so far, claims that separated forms of code-switching are related to caudate changes could be based only on the proxy that such code-switching forms are typically used more often in a specific interactional context. The current findings corroborate this notion, using a direct measure of the frequency types and revealing that more pronounced caudate volume effects are indeed linked to the separated forms of code-switching. Our results also suggest that the degree of separation of both languages in a code-switch has a graded effect on the extent to which caudate adapts.

We found that thalamus volumes increased with more frequent engagement in intersentential code-switching and alternation, which largely corroborates the observed patterns in caudate. Thus, and in line with our predictions, thalamus 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 thalamus 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 adaptions in the thalamus. Alternation has also been previously linked to reactive inhibitory control processes (Hofweber et al., 2020), b 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 Inhibitiory 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.

4.4.3 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 & Witteman, 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 thalamus volumes, whereas for caudate volumes, the effect of directionality appears to be more complex.

Caudate volumes 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 caudate volume effects only for the most separated types of code-switching: intersentential code-switching and alternation. This pattern supports the notion that the caudate is more involved in switching from

L1 to L2, as suggested by previous studies which showed increased caudate activation 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 thalamus volumes. 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.

4.4.4 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, 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 caudate 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 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, and for theories on bilingualism-induced neuroplasticity, such as the DRM. 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. Finally, these findings support the notion of the DRM that structural adaptations brought about by bilingual experiences are dynamic, depending on the quantity and quality of such experiences. However, the DRM did not formulate explicit predictions of the dynamicity of effects of isolated patterns in bilingual language use. The current study expands on the DRM by modelling dynamic structural effects in the brain induced by subtly different code-switching habitual patterns, showing that even at this level, specific bilingual experiences may differentially alter volumetric trajectories in subcortical structures.

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.

CHAPTER 5

GENERAL DISCUSSION

It is well established that bilingualism brings about structural brain adaptations (Danylkiv & Krafnick, 2020). In this view, bilingualism adds to a list of cognitively demanding experiences which surpass the limits of the brain's existing functional capabilities and cause its structure to adapt to handle the experience effectively (Pliatsikas, DeLuca, et al., 2020). As discussed in detail earlier, in the case of bilingualism, the related cognitive demands are widely attributed to the control of two concurrently activated languages in one's mind (Kroll et al., 2021). The regions that are prone to adaptations due to bilingual language use are part of language processing and cognitive control networks (Tao et al., 2021). Moreover, a growing number of studies has emphasised the need to acknowledge that bilingualism encompasses a rich variety of experiences with potential effects on the brain, and to view any related structural brain changes as consequences of specific language use patterns and their combined effects (de Bruin & Della Sala, 2016; DeLuca et al., 2019; Pot et al., 2018). However, given the unflagging emergence of new results which are still often inconsistent in terms of the location, direction, magnitude and latency of neuroanatomic effects, a broader understanding of bilingualism-induced neuroplasticity may still be needed (Pliatsikas, 2020). The inconsistencies and continuously increasing complexity of factors examined to disentangle the sources of brain adaptations in bilingual populations have been interpreted by some as an indication that if bilingualism induces any effects, these occur only under very specific, undetermined circumstance (K. R. Paap et al., 2015). At the same time, the authors have seen this as a reason to claim that this research program should probably be dismissed (K. R. Paap et al., 2015). This thesis, on the other hand, views the consideration of complexity as indicative of a field that is raising the bar ever further and strives for explanations which are not necessarily simple, but rather adequate.

The current project set out different ways in which the field of bilingualism-induced neuroplasticity could continue the shift of its investigative aims towards higher levels of complexity. The main argument built here is that the field should keep investigating the extent to which structural adaptations are moderated by bilingual experiences and their interactions, while considering types of experiences that have been largely overlooked so far. For these purposes, a large sample of bilinguals with a wide range of bilingual experiences was studied, including interpreters and translators. Critically, the evidence presented here highlights that a successful deconstruction of seemingly inconsistent neuroanatomic changes requires a comprehensive incorporation of principles of experience-dependent neuroplasticity (Lövdén et al., 2020). The contributions highlighted here will be discussed in more detail.

This thesis presented evidence which established that non-linear volumetric trajectories in subcortical structures are linked to quantified bilingual experiences (Chapter 2, 3, and 4). Five important methodological decisions achieved this. First, continuous measures of bilingual experiences were used as main predictors of grey matter volumes, focusing on their effects *within* bilinguals. In doing so, the current project directly followed a line of research that argues for the departure from the canonical methodology of mere categorical comparisons between monolinguals and bilinguals and the adoption of assessment of bilingualism-related effects on a continuum (DeLuca et al., 2019; Luk & Bialystok, 2013). Second, the consistent use of generalised additive mixed models (either in frequentist inference as in Chapters 2 and 4 or in Bayesian inference as in Chapter 3) allowed for modelling non-linear relationships between trajectories of regional brain volumes and bilingual experiences. Third, the language pair was kept constant (Chapters 2, 3, and 4). We could therefore avoid the noise that is present in studies in which bilinguals from different language pairs are involved and reveal the effect of bilingual experiences on the brain more clearly. Fourth, we used an innovative way to measure participants' code-switching practices, which allowed for detailed measurements of one specific aspect of participants' bilingual experiences (Chapter 4). Fifth, all the participants came from the same environment, that is their home country, Czechia, or they have spent there most of their life and had a native-like level of the dominant language, Czech. Therefore, we could minimise the effects of the community language practices.

Overall, the findings support the view that bilingualism-related adaptations are dynamic and yet highly regular when viewed through the prism of experience-based neuroplasticity. Notably, these results offer direct support to an existing model which formulated predictions about dynamic effects of bilingual experiences on brain structural adaptations, *the Dynamic Restructuring Model* (DRM; Pliatsikas, 2020).

This project went beyond the mere assumption of the dynamicity of structural brain effects. Instead, following the DRM, it formulated and tested explicit a-priori predictions about the shape of the trajectories of volumetric changes induced by general bilingual experiences (Chapters 2 and 3). The data revealed trajectories of grey matter volumes which suggest that bilingual experiences can trigger expansion-renormalisation patterns in three subcortical structures known to be relevant for bilingual language control, i.e. caudate, nucleus accumbens, and putamen. That is, in less experienced bilinguals, grey matter volumes of these structures seem to increase with growing bilingual experiences, whereas these volumes decrease in highly experienced bilinguals. Thus, the renormalisation of grey matter volumes is likely the result of optimisation of the cognitive processes enabling successful control for two languages in bilinguals who had enough opportunity to engage in bilingual language control and become efficient in it.

The expansion-renormalisation trajectory induced by general experiences applied only to the caudate nucleus and the nucleus accumbens (Chapter 2), whereas significant effects observed in other subcortical structures, i.e., the putamen and thalamus, were positive and linear. This is significant as it is suggestive of implications for the time course of the neural adaptations, which is linked to the neuroplasticity principle that renormalisation requires long and sufficiently intense engagement in the given process (Wenger, Brozzoli, et al., 2017). Concerning the caudate, these findings corroborate existing empirical evidence and theoretical notions that the caudate is intensely relied on from the beginning of the onset of second language acquisition, and they highlight the importance of this region for bilingual language use (Green & Abutalebi, 2013; Pliatsikas, 2020; Pliatsikas et al., 2017). As for the accumbens, for which the adaptations have been less studied, the current results prompt further investigation of this region and its importance for bilingualism, with perhaps a particular focus on functional collaboration of the accumbens with the neighbouring caudate nucleus.

In line with the assumption that any effects on structure will be conditioned not only by the quantity but also by the quality of bilingual experiences (Pliatsikas, 2020), the consistency of the effects of general bilingual experiences was tested in three groups of bilinguals who differed in terms of the professional bilingual practices in which they engage (Chapter 3). The expansion-renormalisation trajectory was found for the caudate nucleus in translators and interpreters, but not in non-professional bilinguals. Furthermore, an expansion-renormalisation pattern of grey matter volumes was also found in the putamen in interpreters. By contrast, the trajectory of the caudate and the putamen observed in non-professional bilinguals implied continuous increases with an absence of any renormalisation. The importance of these findings is at least two-fold. First, they imply that the purposes for which bilinguals use their languages determine which neural resources will be utilised and to what extent, which in turn determines the locations, magnitudes, and time courses of the associated neuroanatomical effects. Specifically with respect to the interpreters, the functional dissociation of the caudate and the putamen has been proposed in *the Neurocognitive model of simultaneous* (Hervais-Adelman & Babcock, 2020). These findings support this model and suggest that the different functionality of these regions also has distinct structural correlates. Second, investigation of the heavily understudied group of exceptionally experienced bilinguals can inform theories that attempt to explain how the brain adapts to extremely demanding bilingual experiences and likely also arduous cognitive demands in general. The current findings confirm the DRM's predictions of decreases in grey matter volumes in the caudate in bilinguals at the peak of their efficiency. Moreover, the replication of such a pattern for the putamen in interpreters invites the extension of the hypotheses devised by the DRM to include this region (Pliatsikas, 2020). Ultimately, these findings emphasise that brain structural adaptations are conditioned by multi-causality of various factors, which was tested here in the case of combined effects of bilingual experiences common to all bilinguals and professional bilingual practices.

An example of a combination of two interacting bilingualism-related factors is language background and switching practices (Beatty-Martínez et al., 2020). Specifically, the language environment in which bilinguals operate has been posited as a determinant of the opportunity to engage in qualitatively different switching practices, the control of which relying on distinct cognitive control mechanisms (Green & Abutalebi, 2013). Indeed, a bulk of empirical studies has also provided evidence that suggests that various bilingual interactional contexts condition performance on cognitive tasks and give rise to the emergence of neural adaptations in brain regions subserving cognitive control processes (Beatty-Martínez & Dussias, 2017; DeLuca et al., 2019). The results from Chapter 4 confirm the broader implications of this line of research by revealing that code-switching was related to neuroanatomical changes in cognitive control hubs. However, the present data uncovered distinct neural changes linked to habitual use of various code-switching types in different directions, while the interactional context was kept constant. Such findings do not disprove that language background can serve as a valuable proxy of neurocognitive effects of switching practices. However, they do highlight that even bilinguals coming from contexts where code-switching is not expected to be a community-wide discourse mode do engage in a rich variety of its forms and that their code-switching practices have measurable and variable consequences on the brain structures subserving them. These findings also have theoretical implications for existing models on cognitive demands imposed by switching practices. Specifically, the data suggests that the involvement of cognitive control in intrasentential code-switching is likely higher than previously hypothesised in the *Adaptive Control Hypothesis* (ACH; Green & Abutalebi, 2013). Moreover, the results revealed graded patterns of structural adaptations linked to the degree of separation between two languages in various code-switching types, which offers support to the *Inhibitory Control Continuum* model (ICC; Treffers-Daller, 2009). Furthermore, the findings in Chapter 4 prompt this model to be extended to include intersentential code-switching as the most demanding cognitively demanding code-switching type. In all, the current results underline the importance of measuring actual habitual code-switching patterns in future studies on bilingualism-induced neuroplasticity.

In summary, the findings of the current project discussed here affirm that the field should move forward with a detailed investigation of bilingualism-induced effects while taking on board the existing knowledge of the general principles of experiences-dependent neuroplasticity. The current project is far from exhaustive in terms of the methodologies and bilingualism-related experiences considered, which signals the work that lies ahead, as will be explored through several suggestions for future research.

5.1 FUTURE DIRECTIONS

5.1.1 LANGUAGE PAIRS

It has been pointed out repeatedly in this thesis that bilingualism is essentially a social and linguistic phenomenon. Building on these two prominent attributes, studies on the effects of bilingual language use on the brain should consider which languages the participants use and their status in the given environment. From a sociolinguistic view, languages are not perceived only as mere computational or communication systems but also as tokens of societal prestige. Language use patterns can be highly impacted by the perceived appropriateness of using one language over another and can lead to increased engagement in specific bilingual behaviours or their avoidance (Jongbloed Faber, 2016; Treffers-Daller, 2002).

Furthermore, typological proximity has also been proposed as a modulating factor of levels of cognitive control, though the direction of the effects is under discussion (Puig-Mayenco et al., 2020). A closely related L1 could facilitate the use of the L2 due to the high mutual intelligibility and large number of cognates, giving rise to high levels of co-activation. On the other hand, the more similar the languages are, the more inhibitory control and monitoring resources may be required to distinguish between two similar mental representations and to subsequently suppress the less appropriate one (Rothman, 2015), which could also have variable effects on brain structure (Antoniou & Wright, 2017).

The issues mentioned above emphasise that the neurocognitive effects of different language pairs is an empirical question that deserves further investigation. Although this question has not been addressed directly here, we controlled for variance from linguistic proximity by keeping the two languages constant (Czech and English; Chapter 4), or by minimising the proximity effects by including L1 speakers of the same language family (Slavic languages and English, Chapter 2 and 3). This opens up the possibility to compare the current results with future studies on language pairs with different typological distances, but with otherwise the same designs, which would constitute a step forward in singling out the effects of typological proximity.

5.1.2 LONGITUDINAL STUDIES WITH MULTIPLE POINTS OF DATA ACQUISITION

Most evidence about the neuroanatomical effects of bilingualism comes from cross-sectional studies. Crosse-sectional studies have benefits in terms of time and resources needed and no risk of degradational data quality due to participant dropouts. However, these studies typically have limitations, as there are many factors that must be addressed before their findings can be extrapolated. Such limitations are particularly apparent when investigating the effects of bilingual experiences from a duration-based perspective. As posited by the DRM, which constitutes a theoretical basis for the current project, it is the duration of an experience alongside its intensity which governs the emergence and fashion of any structural effects. However, it is clear that in the case of sustained experiences, the continuity and quality of any experience-based factors will vary on a subject-to-subject basis. Cross-sectional studies cannot by virtue of their between-subject comparisons tell apart which part of the observed effects is linked to the bilingual experiences and which is coming from individual, often bilingualism-unrelated differences as the data are averaged across individuals. In contrast, longitudinal studies enable to control for extraneous variables more effectively. Comparing data from the same participant collected at different times allows the establishment of an actual baseline of the neural architecture and details its true development over time. Indeed, existing longitudinal studies in the field of bilingualism have proven invaluable in informing existing theories on the neurological impact of several weeks of active second language learning or up to three years of bilingual language use (Deluca et al., 2019; Ilg et al., 2008; Van der Linden et al., 2018, inter alia). However, it follows from the main premise that experience-dependent changes are dynamic and non-linear, that two imaging sessions at the start and the end of the study period, mostly used in the existing research, cannot provide insights on the time course or trajectory of bilingualism-induced structural brain changes. Indeed, results from a recent training study on left-handed writing with 18 measurement points affirm that such an approach is able to reveal patterns of dynamic grey matter changes (Wenger, Kühn, et al., 2017). Therefore, if future studies are to appropriately capture the non-linear adaptions brought about by bilingual experiences over time, it is timely that bilingualism research engages with more complex longitudinal study designs with measurements at multiple points in time, accompanied by a detailed assessment of language use patterns.

5.1.4 MACHINE-LEARNING AND PREDICTIVE MODELLING

Linking brain structure and behavioural patterns is a challenging task, and the multifactorial nature of bilingualism sets the bar even higher. Throughout this thesis, several possible ways have been described for how the various factors could be measured in isolation, confounder-adjusted, controlled for by keeping the sample uniform, or combined in a single composite score. These approaches were put in place because analytical methods used in this project are bound by computational limits on the number of predictors and confounding variables that can be modelled to prevent overfitting. Effectively, such methods allow only for tests of a limited number of factors at a time and limit the ability to reveal the relative contribution of these factors and their interactions on grey matter volumes.

Current developments in statistical and computational tools offer alternatives that might confirm previously identified effects of bilingual experiences and model estimates about the relative contribution of the individual bilingualism-related factors on the brain. For example, the emergent use of machine-learning approaches would allow the selection of the most prominent factors among many and identify the extents to which they interact or collineate with each other (Varoquaux & Thirion, 2014). While the use of these methods is in its infancy, several studies have been able to implement them to investigate cellular correlates of volumetric brain changes (Asan et al., 2021), the link between lifestyle and biological determinants of grey matter properties in general (Galiè et al., 2020), and the correlation of grey matter volumes with intelligence (Hilger et al., 2020). If machine-learning based predictive modelling could be used to elucidate structural correlates of a high-end cognitive construct such as intelligence, it should be worthwhile to explore how these methods could help in the context of bilingualism-induced neuroplasticity.

5.2 CONCLUSION

The work in this thesis underlines the transformative power of the demanding experience of bilingualism on the neuroanatomy of the human brain. Following from developments in a field that is currently embracing the complexity of bilingualism itself, this project examined a variety of quantified continuous experience-based bilingual factors and their combined effects on brain structure. This thesis provides concrete findings on the dynamic effects of bilingual language use on grey matter volumes of subcortical regions known to subserve language processing and cognitive control. The dynamicity of these effects was mirrored in volumetric trajectories spanning increases and decreases of the regional brain volumes. Importantly, by viewing the observed effects through the prism of experience-based neuroplasticity, this work aligns with emergent notions that nuanced assessment of the complex phenomenon of bilingualism might lead to the discovery of highly regular relationships. In this view, this thesis highlights the need to adopt the assumption of non-linearity in future studies on the effects of bilingual experiences on brain structure. While this work investigated only a fraction of this subject, it paves a possible path contributing to the exploration of a variety of bilingual populations to identify bilingual phenotypes and experiences with conclusive and regular effects on the structure of the brain.

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APPENDIX A: RESULTS FROM THE FIRST-LEVEL MODELS (CHAPTER 2)

Separate GAMs for each level of hemisphere as reference levels in each region of interest, looking at the effects of BCS xHemisphere interaction on the subcortical brain volumes)

CAUDATE

Reference level of Hemisphere	Left	Right
BCS	0.001	>0.001
Age	0.003	0.003
Hemisphere	0.008	0.009
BCS x hemisphere	0.375	0.780

ACCUMBENS

Reference level of Hemisphere	Left	Right
BCS	0.038	0.047
Age	0.374	0.247
Hemisphere	<0.001	<0.001
BCS x hemisphere	0.378	0.868

PUTAMEN

Reference level of Hemisphere	Left	Right
BCS	0.086	0.015
Age	0.013	0.013
Hemisphere	<0.001	<0.001
BCS x hemisphere	0.286	0.281

PALLIDUM

Reference level of Hemisphere	Left	Right
BCS	0.553	0.259
Age	0.468	0.527
Hemisphere	0.465	0.465
BCS x hemisphere	0.0415*	0.0421*

THALAMUS

Reference level of Hemisphere	Left	Right
BCS	0.016	0.019
Age	0.055	0.065
Hemisphere	<0.001	<0.001
BCS x hemisphere	0.918	0.941

APPENDIX B: ASSESSMENT OF GAMS FITS USING FUNCTION GAM.CHECK() OF THE MGCV R PACKAGE. (CHAPTER 2)

Model diagnostics: BCS as predictor of caudate volumes (second-level model)
Model: *gam(Volume ~ s(subject, bs= "re") + s(Age) + s(Gender , bs = "re") + Hemisphere + s(BCS), data = dat.caudate, method = “REML”)*

Smooth term	K (number of basis functions)	Estimated degrees of freedom	k-index	p-value of significant patterns in residuals
Age	10	1.00	1.09	0.91
BCS	10	3.32	1.36	1.00

Model diagnostics: BCS as predictor of accumbens volumes (second-level model)
Model: *gam(Volume ~ s(subject, bs= "re") + s(Age) + s(Gender , bs = "re") + Hemisphere + s(BCS), data = dat.accumbens, method = “REML”)*

Smooth term	K (number of basis functions)	Estimated degrees of freedom	k-index	p-value of significant patterns in residuals
Age	10	1.68	0.98	0.32
BCS	10	1.96	1.30	1.00

Model diagnostics: BCS as predictor of putamen volumes (second-level model)
Model: *gam(Volume ~ s(subject, bs= "re") + s(Age) + s(Gender , bs = "re") + Hemisphere + s(BCS), data = dat.putamen, method = “REML”)*

Smooth term	K (number of basis functions)	Estimated degrees of freedom	k-index	p-value of significant patterns in residuals
Age	10	1.00	0.95	0.19
BCS	10	1.00	1.33	1.00

Model diagnostics: BCS as predictor of thalamus volumes (second-level model)
Model: *gam(Volume ~ s(subject, bs= "re") + s(Age) + s(Gender , bs = "re") + Hemisphere + s(BCS), data = dat.thalamus, method = “REML”)*

Smooth term	K (number of basis functions)	Estimated degrees of freedom	k-index	p-value of significant patterns in residuals
Age	10	1.95	1.10	0.93
BCS	10	1.00	1.42	1.00

APPENDIX C: STIMULI FOR THE CZECH-ENGLISH CODE-SWITCHING FREQUENCY TASK (CHAPTER 4)

Direction	**Type**	
cs -> en	INS	Tady vidíš, že ona je in need of pomoc.
cs -> en	INS	Pořebuje eintrainment na celý večer.
cs -> en	INS	Dostal na to anti-inflammatory léky.
cs -> en	INS	Zaplatil jsem holding deposit včera ráno.
cs -> en	INS	Napsal slohovku v takovem subjectu těžkým.
cs -> en	INS	Ale Bobši, ty můj wingman zkrátka být musíš.
cs -> en	INS	Přines si speaker svůj, já svůj taky přinesu.
cs -> en	INS	Nám o external examiners taky řekli.
cs -> en	INS	Říkali nám, že prý můžeš dispute tvůj result.
en -> cs	INS	It's official! Jaro coming! I am so happy!
en -> cs	INS	I will stay nearby the stall with německý hotdogs.
en -> cs	INS	I need to go to Leeds na prohlídku of the flat.
en -> cs	INS	I've heard that this cvičení is pretty difficult.
en -> cs	INS	A book spadla on the table and destroyed the glass.
en -> cs	INS	We are supposed to potkat se for the dinner, right?
en -> cs	INS	They just decided not to organise svatba first.
en -> cs	INS	Maybe you should cut it with vidličkou just like this.
en -> cs	INS	We did a závod in the street with cars on Wednesday.
cs -> en	ALT	Chci si pak koupit for example byt s balkonem.
cs -> en	ALT	Vážně jsem teď úplně socially satisfied.
cs -> en	ALT	Ty fotky ze včerejška s Dominikem, jsou gold .
cs -> en	ALT	Budu tam tak za 30 minut, budete tam still?
cs -> en	ALT	Už je to dlouho, you know, co jsem něco četl.
cs -> en	ALT	Koukal na mě like: `hm, to není dobrá škola."
cs -> en	ALT	Barvili jsme vajíčka alright s holkama.
cs -> en	ALT	Po letech jsem se zbavil auta a bought a bike.
cs -> en	ALT	Nech ho teď chvíli sedět, because it is raining.
en -> cs	ALT	I am struggling, the queues at the front are horrible, fakt.
en -> cs	ALT	I've met her again in Prague, mojí kamarádku.
en -> cs	ALT	I am waiting outside of the house, jako vždycky
en -> cs	ALT	The boy felt rather funny, you know, opouštěně.
en -> cs	ALT	He went home, vyzvednout nějaké oblečení.
en -> cs	ALT	She probably realized it too, ale kdo ví.
en -> cs	ALT	She couldn't stand his mother, co jsem tak slyšela.
en -> cs	ALT	We've never been to France, but I'd like to go, víš co.
en -> cs	ALT	He was surprised a jakože: `Where are you going?'

cs -> en	DENSE CS	Jsem transport and I’m a van driver, který drive a van.
cs -> en	DENSE CS	Já pak pick up the mail, když máš contract with the post.
cs -> en	DENSE CS	Vyzvedávám mails every day a pak to jde out.
cs -> en	DENSE CS	Pak jsme hangoutovali with her a went home.
cs -> en	DENSE CS	Maria šla po ulici a já jsem followed her.
cs -> en	DENSE CS	Muselo tu rained, as ty ulice are mokré.
cs -> en	DENSE CS	V poledne si dáme nějakou break to relax properly.
cs -> en	DENSE CS	Oni se s ní then nebotherovali at all.
cs -> en	DENSE CS	Minulý rok, it used to sněžívat in Prague víc.
en -> cs	DENSE CS	This is a film Tadeáš prý did not like tolik.
en -> cs	DENSE CS	We are going on chatu for a wholý víkend.
en -> cs	DENSE CS	Eat it with rukou because it chutná mnohem líp.
en -> cs	DENSE CS	I didn't like it jako dítě, ale now jo.
en -> cs	DENSE CS	Last night he neslept at all, but byl ok with that.
en -> cs	DENSE CS	It's not that he didn't nevědel nic, věděl dost.
en -> cs	DENSE CS	He did zorganizoval ten workshop very well.
en -> cs	DENSE CS	Concentrate-li se, you will be able to see it.
en -> cs	DENSE CS	The song I would have zpíval was not on the list.
cs -> en	intersentential	Slyšel jsem jak mamce říká, "let's go to the pub."
cs -> en	intersentential	Seděl jsem za řidičem. I didn't have the belt.
cs -> en	intersentential	Musíme si srovnat datumy - it's been too long.
cs -> en	intersentential	Můžeme se potkat, I don't want to be alone
cs -> en	intersentential	Jan nakonec taky přísel, then I saw him too.
cs -> en	intersentential	Můžou si dát něco jiného, do they like Thai?
cs -> en	intersentential	Zakřičel nahlas Dobré ráno, but he was late.
cs -> en	intersentential	Cože tady stojí napsáno? Save the children?
cs -> en	intersentential	Dobře, uděláš to ty, then they will believe it.
en -> cs	intersentential	I do think, že se příště musí obléct lépe.
en -> cs	intersentential	Who thinks it isn't true? Tak znovu, who thinks that?
en -> cs	intersentential	They are very scary. Pojďme si to teď sepsat.
en -> cs	intersentential	They come here. Pak zase budou muset jít domů.
en -> cs	intersentential	She brought the lamb.Teď je to schovaný v ledničce.
en -> cs	intersentential	No way! Její snoubenec je naštvaný říkáš?
en -> cs	intersentential	Thank you for the great dinner, it was delicous.
en -> cs	intersentential	You need to play all your cards. Pak můžeš sázet dál.
en -> cs	intersentential	He was always like this. He entertained people and laughted.

APPENDIX D: REPORT OF ALL PREDICTING VARIABLES IN GAMMS (CHAPTER 4)

MODELS PREDICITING CAUDAL VOLUMES

OVERALL CS FREQUENCY (BOTH DIRECTIONS)	p-value
CS frequency	<0.001
Gender	0.478
Subject (random effect)	<0.001
Age	0.003

OVERALL CS FREQUENCY (EN->CS)	p-value
CS frequency	<0.001
Gender	0.516
Subject (random effect)	<0.001
Age	0.001

OVERALL CS FREQUENCY (CS->EN)	p-value
CS frequency	0.001
Gender	0.543
Subject (random effect)	<0.001
Age	0.004

INTERSENTENTIAL (BOTH DIRECTIONS)	p-value
CS frequency	<0.001
Gender	0.650
Subject (random effect)	<0.001
Age	0.001

INTERSENTENTIAL (CS->EN)	p-value
CS frequency	<0.001
Gender	0.491
Subject (random effect)	<0.001
Age	0.005

INTERSENTENTIAL (EN->CS)	p-value
CS frequency	<0.001
Gender	0.896
Subject (random effect)	<0.001
Age	<0.001

ALTERNATION (BOTH DIRECTIONS)	p-value
CS frequency	<0.001
Gender	0.439
Subject (random effect)	<0.001
Age	0.001

ALTERNATION (CS->EN)	**p-value**
CS frequency	0.014
Gender	0.791
Subject (random effect)	<0.001
Age	0.013

ALTERNATION (EN->CS)	**p-value**
CS frequency	<0.001
Gender	0.789
Subject (random effect)	<0.001
Age	0.003

INSERTION (BOTH DIRECTIONS)	**p-value**
CS frequency	0.033
Gender	0.714
Subject (random effect)	<0.001
Age	0.006

INSERTION (CS->EN)	**p-value**
CS frequency	0.022
Gender	0.639
Subject (random effect)	<0.001
Age	0.002

INSERTION (EN->CS)	**p-value**
CS frequency	0.165
Gender	0.859
Subject (random effect)	<0.001
Age	0.014

DENSE CS (BOTH DIRECTIONS)	**p-value**
CS frequency	0.059
Gender	0.755
Subject (random effect)	<0.001
Age	0.004

DENSE CS (CS->EN)	**p-value**
CS frequency	0.036
Gender	0.630
Subject (random effect)	<0.001
Age	0.003

DENSE CS (EN->CS)	**p-value**
CS frequency	0.077
Gender	0.684
Subject (random effect)	<0.001
Age	0.005

MODELS PREDICITING THALAMIC VOLUMES

OVERALL CS FREQUENCY (BOTH DIRECTIONS)	p-value
CS frequency	0.114
Gender	0.414
Subject (random effect)	<0.001
Age	0.178

OVERALL CS FREQUENCY (EN->CS)	p-value
CS frequency	0.083
Gender	0.451
Subject (random effect)	<0.001
Age	0.164

OVERALL CS FREQUENCY (CS->EN)	p-value
CS frequency	0.140
Gender	0.369
Subject (random effect)	<0.001
Age	0.198

INTERSENTENTIAL (BOTH DIRECTIONS)	p-value
CS frequency	0.002
Gender	0.028
Subject (random effect)	<0.001
Age	0.023

INTERSENTENTIAL (CS->EN)	p-value
CS frequency	0.017
Gender	0.055
Subject (random effect)	<0.001
Age	0.043

INTERSENTENTIAL (EN->CS)	p-value
CS frequency	0.029
Gender	0.088
Subject (random effect)	<0.001
Age	0.078

ALTERNATION (BOTH DIRECTIONS)	p-value
CS frequency	0.038
Gender	0.500
Subject (random effect)	<0.001
Age	0.174

ALTERNATION (CS->EN)	p-value
CS frequency	0.323
Gender	0.283
Subject (random effect)	<0.001
Age	0.225

ALTERNATION (EN->CS)	**p-value**
CS frequency	0.016
Gender	0.41
Subject (random effect)	<0.001
Age	0.112

INSERTION (BOTH DIRECTIONS)	**p-value**
CS frequency	0.224
Gender	0.355
Subject (random effect)	<0.001
Age	0.198

INSERTION (CS->EN)	**p-value**
CS frequency	0.159
Gender	0.399
Subject (random effect)	<0.001
Age	0.138

INSERTION (EN->CS)	**p-value**
CS frequency	0.605
Gender	0.285
Subject (random effect)	<0.001
Age	0.289

DENSE CS (BOTH DIRECTIONS)	**p-value**
CS frequency	0.099
Gender	0.424
Subject (random effect)	<0.001
Age	0.122

DENSE CS (CS->EN)	**p-value**
CS frequency	0.120
Gender	0.420
Subject (random effect)	<0.001
Age	0.133

DENSE CS (EN->CS)	**p-value**
CS frequency	0.126
Gender	0.348
Subject (random effect)	<0.001
Age	0.129

APPENDIX E: ESTIMATION OF EFFECTS OF LSBQ IN EACH HEMISPHERE; LSBQ X HEMISPHERE INTERACTION (CHAPTER 3)

CAUDATE – NON-PROFESSIONAL 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 – NON-PROFESSIONAL BILINGUALS

Reference level of Hemisphere	Left	Right
Age	0.006	0.007
LSBQ x hemisphere	0.372	0.907

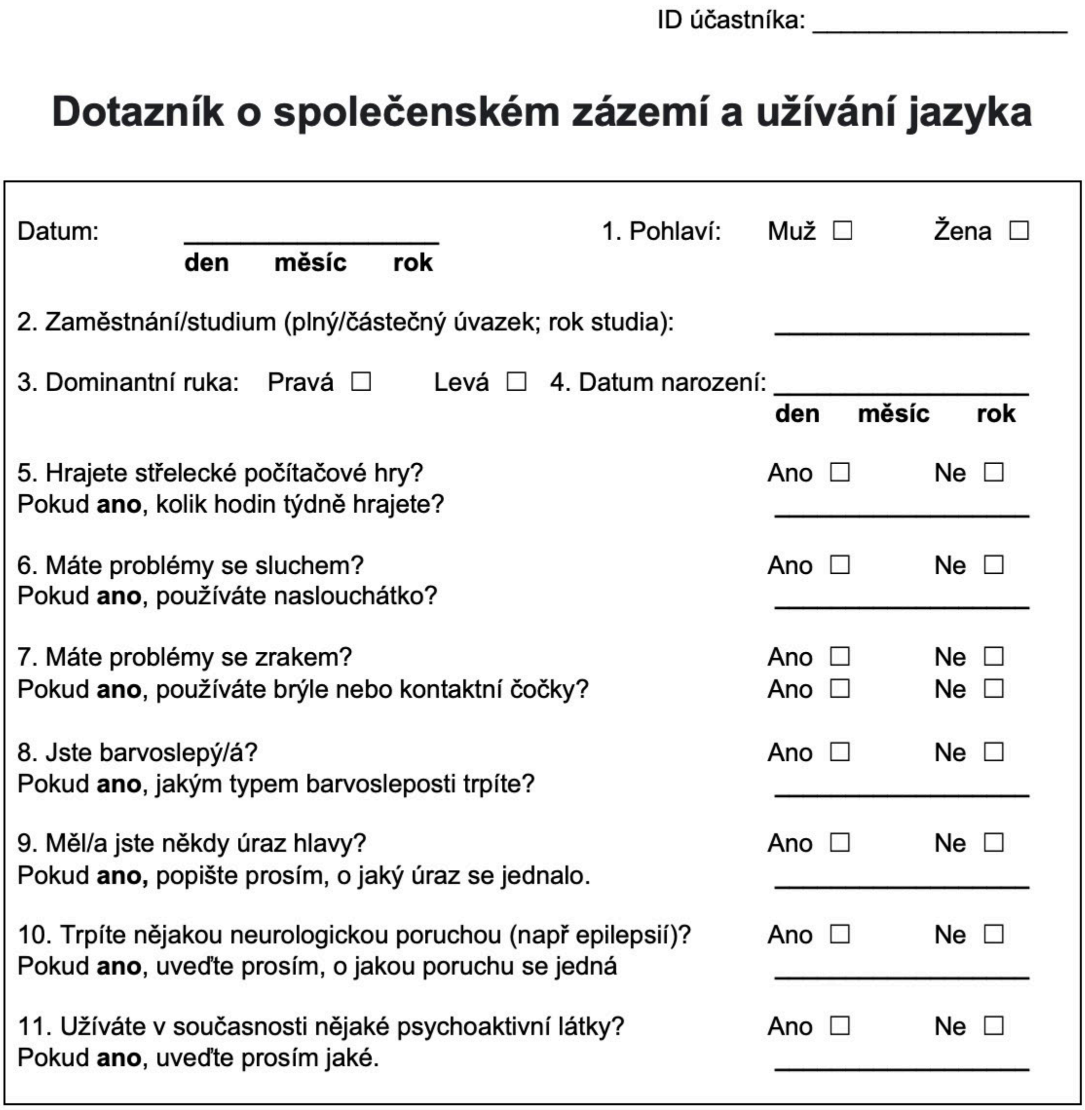
PUTAMEN – TRANSLATORS

Reference level of Hemisphere	Left	Right
Age	0.213	0.213
LSBQ x hemisphere	0.882	0.787

PUTAMEN – INTERPRETERS

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

APPENDIX F: LANGUAGE SOCIAL BACKGROUND QUESTIONNAIRE (CZECH VERSION)



ID účastníka: ___________________

Dotazník o společenském zázemí a užívání jazyka

Datum: ___________________ 1. Pohlaví: Muž ☐ Žena ☐
den měsíc rok

2. Zaměstnání/studium (plný/částečný úvazek; rok studia): ___________________

3. Dominantní ruka: Pravá ☐ Levá ☐ 4. Datum narození: ___________________
den měsíc rok

5. Hrajete střelecké počítačové hry? Ano ☐ Ne ☐
Pokud **ano**, kolik hodin týdně hrajete? ___________________

6. Máte problémy se sluchem? Ano ☐ Ne ☐
Pokud **ano**, používáte naslouchátko? ___________________

7. Máte problémy se zrakem? Ano ☐ Ne ☐
Pokud **ano**, používáte brýle nebo kontaktní čočky? Ano ☐ Ne ☐

8. Jste barvoslepý/á? Ano ☐ Ne ☐
Pokud **ano**, jakým typem barvosleposti trpíte? ___________________

9. Měl/a jste někdy úraz hlavy? Ano ☐ Ne ☐
Pokud **ano,** popište prosím, o jaký úraz se jednalo. ___________________

10. Trpíte nějakou neurologickou poruchou (např epilepsií)? Ano ☐ Ne ☐
Pokud **ano**, uveďte prosím, o jakou poruchu se jedná ___________________

11. Užíváte v současnosti nějaké psychoaktivní látky? Ano ☐ Ne ☐
Pokud **ano**, uveďte prosím jaké. ___________________

ID účastníka: ___________________

12. Uveďte prosím nejvyšší dosažené vzdělání a zaměstnání obou Vašich rodičů. Dále uveďte jejich mateřský jazyk (případně více jazyků).

Matka	Otec
1. _____ Základní vzdělání	1. _____ Základní vzdělání
2. _____ Učňovské vzdělání	2. _____ Učňovské vzdělání
3. _____ Středoškolské s maturitou	3. _____ Středoškolské s maturitou
4. _____ Vyšší odborné/bakalářské	4. _____ Vyšší odborné/bakalářské
5. _____ Magisterské, doktorské a vyšší	5. _____ Magisterské, doktorské a vyšší
Povolání: ___________________	Povolání: ___________________
První jazyk: ___________________	První jazyk: ___________________
Druhý jazyk: ___________________	Druhý jazyk: ___________________
Třetí jazyk: ___________________	Třetí jazyk: ___________________

13. Narodil/a jste se v České republice? Ano ☐ Ne ☐
Pokud **ne**, kde jste se narodil/a? ___________________
V jakém roce jste se přestěhoval/a do České republiky? ___________________ **rok**

14. Žil/a jste někdy na místě, kde čeština nebyla hlavním dorozumívacím jazykem?

Ano ☐ Ne ☐

		od	**do**
Pokud **ano**, kde a jak dlouho?	1. ______________________________________	________	________
	2. ______________________________________	________	________
	3. ______________________________________	________	________
	4. ______________________________________	________	________
		rok	**rok**

ID účastníka: ___________________

15. Uveďte prosím jazyky a dialekty (včetně češtiny), které ovládáte v pořadí dle úrovně plynulosti od nejvyšší k nejnižší.

Jazyk	Kde jste se tento jazyk naučil/a? *(lze zvolit více možností)*	V kolika letech jste se tento jazyk naučil/a? *(pokud jste se jazyk učil/a od narození, uveďte „0“)*	Byly ve Vašem životě období, kdy jste jazyk nepoužíval/a? *Uveďte délku těchto období v měsících/letech.*
1. _______________	☐Doma ☐ Ve škole ☐ Během společenského styku ☐ Jiné: ___________________		
2. _______________	☐Doma ☐ Ve škole ☐ Během společenského styku ☐ Jiné: ___________________		
3. _______________	☐Doma ☐ Ve škole ☐ Během společenského styku ☐ Jiné: ___________________		
4. _______________	☐Doma ☐ Ve škole ☐ Během společenského styku ☐ Jiné: ___________________		
5. _______________	☐Doma ☐ Ve škole ☐ Během společenského styku ☐ Jiné: ___________________		
6. _______________	☐Doma ☐ Ve škole ☐ Během společenského styku ☐ Jiné: ___________________		

ID účastníka: ___________________

Na níže uvedených škálách 0-10 zaznamenejte, jaká je Vaše úroveň níže uvedených dovedností v českém jazyce a druhém jazyce, který ovládáte.

16.1 **Čeština**

	Žádné dovednosti 0	5	Úroveň rodilého mluvčího 10
Mluvení	●		●
Porozumění	●		●
Čtení	●		●
Psaní	●		●

16.2 Z jaké části, když používáte níže uvedené dovednosti, využíváte češtinu? (Např. pokud mluvíte pouze česky, zaškrtněte v kolonce „mluvení“ možnosti „pořád“. Pokud například čtete polovinu knih nebo časopisů v češtině a polovinu v angličtině, zaškrtněte u „čtení“ možnost „v polovině případů“.

	Vůbec	Trošku	V polovině případů	Často	Pořád
Mluvení	☐	☐	☐	☐	☐
Poslech	☐	☐	☐	☐	☐
Čtení	☐	☐	☐	☐	☐
Psaní	☐	☐	☐	☐	☐

17.1 **Druhý jazyk:** ___________________

	Žádné dovednosti 0	5	Úroveň rodilého mluvčího 10
Mluvení	●		●
Porozumění	●		●
Čtení	●		●
Psaní	●		●

17.2 Z jaké části, když používáte níže uvedené dovednosti, využíváte druhý jazyk?

	Vůbec	Trošku	V polovině případů	Často	Pořád
Mluvení	☐	☐	☐	☐	☐
Poslech	☐	☐	☐	☐	☐
Čtení	☐	☐	☐	☐	☐
Psaní	☐	☐	☐	☐	☐

ID účastníka: ___________________

18. Uveďte prosím, který jazyk (čeština nebo druhý jazyk) jste nejčastěji slýchával/a nebo používal/a v níže uvedených obdobích Vašeho života, a to doma i mimo Váš domov.

	Pouze čeština	Převážně čeština	V polovině případů čeština, v druhé polovině druhý jazyk	Převážně druhý jazyk	Pouze druhý jazyk
18.1 Rané dětství	☐	☐	☐	☐	☐
18.2 Předškolní věk	☐	☐	☐	☐	☐
18.3 Základní škola	☐	☐	☐	☐	☐
18.4 Střední škola (do 18 let)	☐	☐	☐	☐	☐

19. Uveďte prosím, který z jazyků (čeština nebo druhý jazyk) nejčastěji používáte při komunikaci s níže uvedenými lidmi.

	Pouze čeština	Převážně čeština	V polovině případů čeština, v druhé polovině druhý jazyk	Převážně druhý jazyk	Pouze druhý jazyk
19.1 Rodiče	☐	☐	☐	☐	☐
19.2 Sourozenci	☐	☐	☐	☐	☐
19.3 Prarodiče	☐	☐	☐	☐	☐
19.4 Další příbuzní	☐	☐	☐	☐	☐
19.5 Partner/ka	☐	☐	☐	☐	☐
19.6 Spolubydlící	☐	☐	☐	☐	☐
19.7 Sousedé	☐	☐	☐	☐	☐
19.8 Přátelé	☐	☐	☐	☐	☐

20. Uveďte prosím, který z jazyků (čeština nebo druhý jazyk) nejčastěji užíváte v níže uvedených situacích.

	Pouze čeština	Převážně čeština	V polovině případů čeština, v druhé polovině druhý jazyk	Převážně druhý jazyk	Pouze druhý jazyk
20.1 Doma	☐	☐	☐	☐	☐
20.2 Ve škole	☐	☐	☐	☐	☐
20.3 V práci	☐	☐	☐	☐	☐
20.4 Společenské aktivity *(setkání s přáteli, kino, …)*	☐	☐	☐	☐	☐
20.5 Náboženské aktivity	☐	☐	☐	☐	☐
20.6 Volnočasové aktivity *(zájmy, sporty, filmy, hraní her, …)*	☐	☐	☐	☐	☐
20.7 Nákupy, restaurace, jiné komerční aktivity	☐	☐	☐	☐	☐
20.8 Veřejné služby, úřady, zdravotnická zařízení, banky	☐	☐	☐	☐	☐

ID účastníka: ___________________

21. Uveďte prosím, který z jazyků (čeština nebo druhý jazyk) nejčastěji užíváte v níže uvedených situacích.

	Pouze čeština	Převážně čeština	V polovině případů čeština, v druhé polovině druhý jazyk	Převážně druhý jazyk	Pouze druhý jazyk
21.1 Čtení	☐	☐	☐	☐	☐
21.2 Psaní e-mailů	☐	☐	☐	☐	☐
21.3 Zprávy na mobilním telefonu	☐	☐	☐	☐	☐
21.4 Sociální sítě *(Facebook, Instagram, Twitter, …)*	☐	☐	☐	☐	☐
21.5 Psaní poznámek, seznamů na nákup	☐	☐	☐	☐	☐
21.6 Sledování TV, poslech rádia *(i YouTube, Seznam TV, iPrima, …)*	☐	☐	☐	☐	☐
21.7 Sledování filmů *(i Netflix, Voyo, iVysílání, …)*	☐	☐	☐	☐	☐
21.8 Surfování na internetu	☐	☐	☐	☐	☐
21.9 Modlení	☐	☐	☐	☐	☐

22. Někteří lidé přepínají v rámci jedné konverzace mezi jazyky, které znají, *(tj. během konverzace v jednom jazyce používají věty nebo slova z jiného jazyka, který ovládají, např.: "By the way, nevíš, v kolik začíná ten fotbalový match?")*. Tomuto jevu se říká "přepínání jazykových kódů". Uveďte prosím, jak často používáte přepínání jazykových kódů v níže uvedených situacích. Pokud neznáte jiný jazyk než češtinu, zvolte možnost "vůbec".

	Vůbec	Trošku	V polovině případů	Často	Pořád
22.1 S rodiči a rodinou	☐	☐	☐	☐	☐
22.2 S přáteli	☐	☐	☐	☐	☐
22.3 Na sociálních sítích *(Facebook, Twitter, …)*	☐	☐	☐	☐	☐

Děkujeme za vyplnění dotazníku!

Bilingualism sculpts the core of the brain: an investigation of experience-dependent neuroplasticity induced by the variable use of two languages

PhD Thesis. School of Psychology and Clinical Language Sciences, University of Reading, Reading, England.

Author: Michal Kořenář

Cover design: Michal Kořenář

Cover photo: Andres Herrera (free to use under the Unsplash License)

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