University of Utrecht

Master Thesis

The Bilingual Neurocognitive Network:

An investigation of Neuroplasticity and Cognitive Performance

Marpessa Rietbergen

3911616

July 2014

Supervisor:

Dr. Frank Wijnen

Uil-OTS

Second Reader:

Dr. Jubin Abutalebi

San Raffaele University

Table of Contents:

Abstract

This thesis presents the literature that has investigated the bilingual advantage across all lifespans. Behavioral studies in connection with neuroimaging research indicate bilinguals manage response selection and inhibition, while facilitating relevant and suppressing irrelevant task goals differently and more effectively than their monolingual peers. These functions are necessary for both bilingual language processing and other cognitive domains, i.e. inhibition and attention. The neuroanatomical structures necessary for bilingual language processing are the neuroanatomical structures that comprise the neurocognitive network necessary for processing in other cognitive domains. Hence, the bilingual advantage is suggested to be influenced by the greater demand placed on the neurocognitive network when handling two language systems, resulting in better cognitive performance. Recent neuroimaging studies have found that the bilingual neurocognitive network is more efficient, exhibiting less functional engagement, and remarkably, changes in brain plasticity.

The current study investigated the bilingual advantage in terms of cognitive performance relative to brain plasticity within the neurocognitive network of lifelong bilinguals. Senior bilingual adults were hypothesized to exhibit plastic differences in the bilateral caudate nucleus compared to monolingual peers. A voxel-based morphology neuroimaging analysis measured gray matter volume in the left and right caudate nucleus, a subcortical region associated with language and cognitive control during task planning and switching. It was predicted that the left caudate would be larger than the right, reflecting the greater processing demands associated with the left hemisphere relative to bilingualism. A flanker task, perceptual nonverbal task that elicits response conflicts, tested cognitive performance in the two language groups. It was predicted senior bilingual adults would outperform monolinguals exhibiting a cognitive advantage. Greater grey matter volume in the left caudate was further hypothesized to correlate with cognitive performance exhibited by senior bilingual adults.

Findings revealed that senior bilingual adults had more grey matter volume in the left caudate than the right, exhibiting a leftward asymmetry. Furthermore, senior bilingual adults outperformed senior monolingual adults indicated by better accuracy and faster reaction times on the flanker task. Grey matter volume in the left caudate of senior bilingual adults correlated with cognitive performance. The results of this study indicate a bilingual advantage in older senior bilinguals over monolingual peers in cognitive performance, and that it may arguably be reflected by the greater grey matter volume in the left caudate.

These findings aim to contribute to the ongoing discussion concerning the cognitive benefits of bilingualism reflected in neuroplasticity and in the cognitive performance of senior adults despite the effect of ageing.

1) Introduction:

Before Peal and Lambert (1962) made their contribution to the linguistic community by providing their account on bilingualism, public opinion was rather critical about the effects of being raised in a bilingual environment. Saer (1923) and Smith (1923) reported that bilingualism was detrimental to the intellectual development of children and that it could hinder functional capacity (as cited by Peal & Lambert, 1962). Concerned that a bilingual environment may unnecessarily confuse or mentally disable the child, parents were discouraged to raise their children as bilinguals. However, in 1962 Peal and Lambert hypothesized "compound" bilingual children (i.e. French-English children), where both languages are learned in the same setting (i.e. Montreal), exhibit greater mental flexibility when confronted with nonverbal cognitive tasks. Part of their research showed 10-year old bilinguals outperforming 10-year old monolinguals during nonverbal tasks that involved the reorganization and categorization of symbolic information, i.e. the Lavoie-Laurendeau picture arrangement tests. Peal and Lambert (1962) suggested that the experience needed to make conceptual associations across languages while shifting between languages provides an "asset" for bilingual children when making new associations and shifting between nonverbal processes. These findings began changing public opinion and the approach taken by the linguistic community to report on cognitive control and executive function in bilingual speakers.

Currently, the "asset" Peal and Lambert refer to has now come to be regarded as the bilingual advantage (Bialystok et al., 2012; Green & Abutalebi, 2013). The advantage that bilinguals come to attain brought on by the added demand placed on executive functions when processing two languages (Bialystok et al., 2012; Abutalebi & Green, 2007; Green & Abutalebi, 2013). The literature indicates that both languages for bilinguals are constantly activated (Brysbaert, 1998; Francis, 1999; Gollan & Kroll, 2001; Kroll & Dijkstra, 2002; Smith, 1997). Once an idea is conceptualized, phonological (i.e. lemmas) and semantic (i.e. lexemes) associations are activated (Roelofs, 1998) in both language (a) and language (b) (Rodriguez-Fornells et al., 2005; Crinion et al., 2006). It is further theorized that through the process of inhibition (Green, 1998) irrelevant information is inhibited and consequently language (x) is demoted and the target language promoted for final processing and production. It is therefore postulated that executive functions that monitor conflict and inhibit response interference in and between languages while shifting between languages (a) and (b), are continuously engaged and presumably more efficient amongst bilinguals. Following this line of reasoning, bilinguals are predicted to have a performance advantage over monolinguals, an advantage when carrying out cognitive tasks that require the engagement of the aforementioned executive functions.

This thesis first explores a few of the behavioral studies that have reported bilingualism influencing executive performance during cognitive control tasks involving conflict and inhibition amongst children, adults, and senior adults compared to monolinguals peers. The inner mechanics involved in cognitive and language control will then be explained. This account provides an overview of the neural correlates that carry out executive functions relative to bilingual language processing and other cognitive processes. Functional neuroimaging studies will be presented in the following section. The thesis presents how patterns of neural activation associated with bilinguals' abilities to switch between two languages follow similar patterns of neural activation observed during conflict (i.e. competing responses) that arises in other cognitive domains. The thesis will then explore structural neuroimaging studies that have reported bilingualism influencing neuroplasticity in regions associated with bilingual language processing. Neuroplasticity are the changes and modifications that occur within the brain, the structural reorganization of grey and white matter in response to behavioral, environmental and processing demands (Draganski et al., 2004, Mechelli et al., 2004). The few studies that have assessed neuroplasticity amongst older bilinguals will be discussed. These studies propose lifelong bilingualism may protect against cognitive decline; however, no studies have investigated neuroplasticity amongst older bilinguals pertaining to regions associated with bilingual language processing. If lifelong bilinguals exhibit neuroplastic differences within the bilingual language control network, it is crucial to investigate whether those differences are associated with greater cognitive control despite ageing deficits.

The current study carried out a behavioral analysis to investigate how well older bilinguals perform during a cognitive control task, Erikson Flanker Task (Erikson & Erikson, 1976), compared to monolingual peers matched for age, gender, education, and mini-mental state examination scores (MMSE). In conjunction with the behavioral analysis, a voxel-based morphometry (VBM) neuroimaging analysis measured grey matter volume (cm^3) within the bilateral caudate nucleus, the left and right caudate nucleus. Among its many functions, the caudate nuclei are also associated with executive functions that deal with response selection and inhibition during task (language) planning. The purpose for the structural analysis was to measure differences in grey matter volume pertaining to the asymmetry of the bilateral structure amongst older bilinguals and older monolinguals. Leftward asymmetry, greater volume in the left caudate, was predicted due to the greater language processing demands associated with bilingualism. The purpose of the conjunction analysis was to investigate whether differences in structural volume observed amongst the two language groups were associated with group performance observed during the cognitive task. It was predicted that older bilinguals would outperform monolinguals, and that bilingual cognitive performance would be associated with leftward asymmetry of the caudate nucleus. This study aims to provide further insight on the bilingual advantage with regard to senior bilinguals and the influence of lifelong bilingualism on neuroplasticity and cognitive performance.

1.1) Bilingualism influences executive function

This section provides an overview of the behavioral findings that have indicated cognitive advantages bilingual children and young adults have over monolinguals, and how these advantages continue to be seen in older adults despite ageing. The literature concerning the negative effects of ageing, maintains that habitual behaviors and established knowledge learned through experience hold up into senior adulthood; however, processes that require executive flexibility are typically the first to be affected by signs of ageing (Bialystok et al., 2004). Nonetheless, despite impending cognitive decline, the following findings report older bilinguals outperforming older monolinguals during cognitive tasks that require greater executive function.

In a study conducted by Bialystok and Viswanatha in 2009, bilingual and monolingual children with matching socioeconomic backgrounds were given a conflict task to test their general executive flexibility. The conflict task specifically assessed performance during conditions that dealt with response suppression, inhibitory control, and switching. Participants included: 30 English-speaking monolingual children (mean age=8.5 years, SD=0.5, range=7.1-9.2, 15 girls); 30 bilingual children (mean age=8.5, SD=0.5, range=7.1-9.4, 15 girls), who spoke English L1 and a second language[1] (the L2); and 30 bilingual children (mean age=8.6, SD=0.5, range=7.1-9.4,18 girls) who spoke Tamil or Telugu L1 and English L2 with no history of immigration[2]. The conflict task was a single and mixed block design prosaccade/anti-saccade Faces Task (Bialystok et al., 2006). Children were shown faces with eyes that would turn red or green, followed by a blank screen that displayed two boxes located on the left and right where an asterisk would appear. If a face with green eyes appeared before the asterisk, children were instructed to press the left or right button pertaining to the left or right box where the asterisk appeared (prosaccade condition). If a face with *red eyes* appeared, children were instructed to press the left or right button pertaining to the left or right box the asterisk *did not* appear in

[1] Bilingual children lived in Canada and spoke an L2: Cantonese, Croatian, French, Hebrew, Hindi, Kannada, Mandarin, Marati, Punjabi, Russian, Tagalog, Telugu, or Urdu (Bialystok & Viswanatha, 2009).

[2] No monolingual children from India were tested due to the lower social ranking of monolingual speakers within Indian

[2] No monolingual children from India were tested due to the lower social ranking of monolingual speakers within Indian society (Bialystok & Viswanatha, 2009).

(anti-saccade condition). The prosaccade (green) and anti-saccade (red) conditions tested executive function that dealt with response facilitation and suppression. To test response inhibition, an eye gaze-shift was added to the stimulus, where red or green eyes would look away (or toward) the box that coincided with the target response. Congruent conditions were trials where green eyes looking toward the asterisk or red eyes looking toward the empty box. Incongruent conditions were trials where green eyes looking toward the empty box or red eyes looking toward the asterisk.

For none gaze-shift blocks, groups performed equally well during single condition blocks. However, bilinguals were faster during mixed blocks on both the red (anti-saccade) and green (prosaccade) conditions, both bilingual groups performed equally well. For gaze-shift blocks, both bilingual groups had faster response times during mixed blocks on congruent and incongruent conditions, and did not differ from one another. Response suppression was the difference between the *green* eye and *red* eye conditions, no significant difference was found between language groups. Response inhibition (i.e. conflict effect) was the difference between mixed blocks *without* gaze shifts (congruent conditions) and mixed blocks *with* gaze shifts (incongruent conditions); both bilingual groups had smaller conflict effects than monolinguals. To assess switching the difference between mixed blocks and single blocks was determined, and monolinguals had greater switching costs and bilinguals had none.

Bilingual and monolingual young-adults (48 subjects; mean age 20 years-old) performed similarly after completing the Faces Task in a 2006 study conducted by Bialystok, Craik, and Ryan. Both the 2006 and 2009 studies report that bilinguals, children and young-adults, have an advantage in terms executive flexibility indicated by their better performance when switching between two tasks, dealing with inhibitory control. However, both bilinguals and monolinguals performed equally well when dealing with response suppression. However, the 2006 study conducted by Bialystok and colleagues also tested a group of older bilingual adults (24 subjects;

mean age 71.3 years-old) extending from English L1 and a range of L2 backgrounds, and a group of older monolingual adults (24 subjects, mean age 70.4 years-old). Older bilinguals significantly outperformed monolingual peers with regard to suppressing irrelevant responses during the Faces Task, indicated by smaller response costs between red and green eye conditions. The 2009 study assessed samples of children from different linguistic and cultural backgrounds indicating that children who are raised in a bilingual environment share similar cognitive advantages, i.e. inhibitory control and switching, and develop these executive functions at a similar rate over time. Both the 2006 and 2009 studies (Bialystok & Viswanatha, 2009; Bialystok, Craik & Ryan, 2006) further indicate that executive function is influenced by bilingualism, and bilingual advantages in executive performance develop over a lifetime. Furthermore, older bilinguals exhibited more developed cognitive advantages than younger bilinguals in terms of response suppression, and exhibit greater cognitive flexibility than monolingual peers despite old age.

1.2) Executive control network

The studies mentioned above are a few of the behavioral studies that assessed the bilingual advantage across different age groups. Behavioral studies allow researchers to identify executive advantages bilinguals exhibit when dealing with non-linguistic cognitive tasks. The following section describes the neuroanatomical underpinnings of the executive functions carried out by the neurocognitive network. The main aim is to map executive functions involved in language processing and other domains of cognitive processing to their neuroanatomical basis.

Abutalebi and Green (2007) proposed a neuroanatomical model comprised of separable regions responsible for the execution of language control and other domains of cognition. Those regions included the prefrontal cortex, the inferior parietal cortex, the anterior cingulate cortex and the basal ganglia. Abutalebi and Green (2007) described the prefrontal cortex as the chief component subserving the executive control network, functioning as a top-down bias mechanism[3] (Desimone & Duncan, 1995; Miller & Cohen, 2001) to carry out executive functions that plan, monitor, correct and execute task relevant goals. The prefrontal cortex is reported to play roles in decision-making, attention, working memory, planning, response inhibition, response suppression, sequencing of behaviors and language. The following cortical and subcortical regions further contribute to the aforementioned executive functions, and complement one another to complete task goals. The inferior parietal cortex maintains goal representations and updates goal information within working memory. The anterior cingulate cortex is involved in attention, monitoring for conflict and errors. The multiple inhibitory and excitatory pathways found amongst the basal ganglia carry out task planning and set shifting or sequence planning, by inhibiting irrelevant information while disinhibiting relevant information to complete one task and to maintain another.

Abutalebi and Green in 2008 proposed a network of neuroanatomical regions that carry out executive functions involved in language switching, the executive demands of monitoring, inhibiting, updating, and shifting between two language systems. The network included the left dorsolateral prefrontal cortex, the anterior cingulate cortex, the basal ganglia, and the bilateral supramarginal gyri. The dorsolateral prefrontal cortex updates linguistic information in working memory, while correcting errors and inhibiting non-target responses. The anterior cingulate cortex monitors response conflicts and signals errors to the prefrontal cortex, to avoid incorrect selection while maintaining target goals in working memory. The researchers proposed that the supramarginal gyri play complementary roles, where the left gyrus helps the prefrontal cortex toward selecting target language goals and the right gyrus against selecting

[3] According to the biased competition model where target and non-target information compete for selection, Desimone & Duncan (1995) propose two mechanisms that aid in the selection of target amongst non-target information. Bottom-top bias mechanism selects salient target information from homogenous non-target information, processing that is more automated. Top-down bias mechanism selects target information relative to stimuli-driven or behavioral goals and requires intention, processing that is more controlled (Miller & Cohen, 2001).

non-target language goals. The basal ganglia are made up of inhibitory interneurons that deal with language planning and switching (caudate nucleus), articulation (putamen), and sequence planning of sensory and motor control (thalamus). Luk, Green, Abutalebi and Gray (2012) carried out a quantitative meta-analysis on neuroimaging studies that reported activity in neural correlates involved in bilinguals' language switching behaviors. Activity was left lateralized and found predominantly in the frontal areas, specifically the left middle frontal gyrus, left inferior frontal gyrus, left middle temporal gyrus, right precentral gyrus, bilateral caudate, and the midline pre-supplementary motor area. Unlike Abutalebi and Green's (2008) predictions, the anterior cingulate cortex and the bilateral supramarginal gyri were not reported. Similar to the anterior cingulate cortex howevere, the midline pre-supplementary motor area monitors and detects errors (Abutalebi et al., 2013), and may initiate and execute speech production during greater linguistic demands that elicit response errors or cause language conflict, i.e. language switching (Lui, Hu, Guo, Peng, 2010).

1.3) Bilingualism influences functional activation

This section describes the relationship between the aforementioned regions and their engagement observed during cognitive and language processing in bilinguals and monolinguals. Specifically, the following neuroimaging studies report on neural activity in the bilingual executive control network engaged during conflict monitoring, response selection and inhibition during cognitive and language control tasks.

In 2010, Luk, Anderson, Craik, Grady and Bialystok conducted an event-related fMRI experiment that assessed 9 English-speaking monolinguals (Mean age=22, range 19-25) and nine bilinguals (Mean age=20, range 19-27) who spoke English L1 and a range of L2's before age 6. This study aimed to identify the shared and distinct neural correlates activated during response selection, the facilitation and suppression of interference, and response inhibition in bilingual and monolingual participants during a cognitive control task. Luk and colleagues (2008) hypothesized that bilinguals differ from monolinguals and rely on neurocognitive regions associated with dual language processing during interference suppression, and that both groups on the motor level would engage similar regions during response inhibition. Executive functions were engaged by testing participants using a flanker task, a perceptual general cognitive conflict task where one responds to the direction of a single target amidst multiple conflicting cues that trigger response conflicts, i.e. slower reaction times (Eriksen & Eriksen, 1976).

The task involved five conditions: baseline, stand-alone red chevron pointing left or right (e.g. >); neutral, red chevron flanked by diamonds (e.g. <> <> > <> <>); congruent, red chevron flanked by chevrons pointing in the same direction (e.g. > > > > >); incongruent, red chevron flanked by chevrons pointing in the opposite direction (e.g. > > > < >); no-go, red chevron flanked by *X*'s (.e.g. X < X X X). There were a total of 40 baseline trials and 480 experimental trials (i.e. neutral, congruent, incongruent, and no-go), and participants responded by pressing a left button, right button, or withheld a response during the no-go condition. The congruent condition was intended to facilitate response selection in choosing the left or right button. The incongruent condition similarly tested response selection that dealt with suppression of interference triggered by the multiple flanking chevrons surrounding the target. Lastly, the no-go condition tested response inhibition at the motor level, where subjects had to override the will to respond to the red chevron, and attend to the multiple *X*'s by not responding.

Two analyses were carried out. The first analysis measured patterns of activation during conflict trials, the incongruent and no-go trials against the baseline trials. Both bilinguals and monolinguals exhibited similar patterns of activation during incongruent and no-go trials, in the right inferior frontal area, left supplementary motor area, left inferior parietal lobule, bilateral cerebellum, bilateral middle and posterior cingulate cortex and middle temporal gyrus. The second analysis measured patterns of activation during experimental conditions, congruent, incongruent and no-go trials. The results revealed different patterns of activation for each language group during incongruent conditions. Bilinguals activated the same regions reported during no-go trials with more widespread activation extending into subcortical areas, the left caudate and left thalamus. Monolinguals exhibited activity that was less widespread and more constrained to the left temporal pole and superior parietal cortex during incongruent trials, engaging a different network to suppress interference.

Accuracy was high during all conditions for both groups. Bilinguals had overall shorter reaction times especially during incongruent trials. The report did not include figures concerning the conflict effect, the difference between reaction times observed during incongruent and congruent conditions. A behavioral-functional conjunction analysis investigated whether correlations between performance and patterns of activation existed within and between groups. The difference in reactions times between incongruent trials and neutral trials indicated that better suppression, i.e. smaller response costs, in bilinguals correlated with activity in the anterior cingulate cortex and the left inferior frontal gyrus. Caudate activity was associated with better facilitation in both groups, i.e. faster reaction times during congruent trials.

The fMRI analysis indicated that both bilinguals and monolinguals rely on the same neurocognitive network when dealing with response inhibition (i.e. no-go conditions). Bilinguals used similar cortical and subcortical regions observed during response inhibition when suppressing interference (i.e. incongruent conditions), while monolinguals engaged fewer more confined regions to suppress interference. Bilinguals engaged a widespread network to execute response inhibition, and used this same network to better manage response selection in non-linguistic cognitive domains. The network included the anterior cingulate cortex, the inferior frontal gyrus, and the left caudate, all regions associated with bilingual language production and language switching (Abutalebi & Green, 2008; Luk et al., 2012).

Abutalebi, Della Rosa, Green, Hernandez, Scifo, Keim, Cappa, and Costa (2012) conducted an event-related fMRI experiment that tested 17 high-proficient German L1 Italian L2 female bilinguals (mean age=23.35, SD±4.59) and 14 Italian female monolinguals (mean age=26.55, SD±4.15). The purpose was to specifically assess the anterior cingulate cortex, the "conflict effect region", and its engagement during both verbal and nonverbal conflict tasks in bilinguals and monolinguals. Verbal and nonverbal conflict tasks engaged the conflict effect region while selecting and inhibiting appropriate responses, facilitating and suppressing interference. Bilinguals were hypothesized to exhibit functional activation within the anterior cingulate cortex while resolving both verbal and nonverbal conflict tasks as proposed in Abutalebi and Green's model (2008).

A picture naming paradigm was used for verbal tasks. A language selection or 'language switching' task that required noun retrieval in the L1 and the L2 was administered to bilinguals, where a green-colored picture required a German (L1) response and a blue-colored picture required an Italian (L2) response. There were 32 picture stimuli, each picture was repeated three times and used during two experimental runs containing 48 trials each. Trials alternated between switch and non-switch trails split across both languages and were in pseudorandom order. Monolinguals were given a lexical selection task that required noun retrieval and verb generations in Italian; a red-colored picture required noun retrieval and a green-colored picture required verb generation. The lexical-selection experimental design followed that of the language-switching experimental design, using the same set of 32 pictures. A flanker task (Erikson & Erikson, 1976) was used for the nonverbal task, where all participants were asked to press a left or right button according to direction of the target arrow being flanked. There were three conditions: congruent, target arrow flanked by four arrows pointing in the same direction, (e.g. → → → → →); incongruent, target arrow flanked by four arrows pointing in the opposite direction (e.g. → → ← → →); and neutral, target arrow flanked by four lines (e.g. – – → – –). All conditions were spread evenly across two experimental runs containing 96 trials each, and each run was administered during two separate experimental sessions.

The behavioral results for the verbal tasks indicated groups had performed similarly. The error rates concerning L1 naming amongst bilingual participants (1.96%, SD±1.32) was comparable to noun retrieval for monolingual participants (2.46%, SD±1.13*)*. There was no significant difference in error rates between L1 and L2 naming (2.76%, SD±1.6) performance. The flanker task revealed a significant difference in reaction times between congruent and incongruent reaction times. Incongruent trials yielded longer reaction times, especially during the first session. The conflict effect between session one and two significantly reduced for bilinguals by 36ms, which indicates bilinguals were faster in the second session.

The fMRI results indicated more activity bilaterally within the anterior cingulate cortex (BA 32) and in the left precentral gyrus (BA 6) amongst bilinguals during language switching trials as opposed to non-switch trials. Monolinguals exhibited marginally greater activity during lexical switching trials compared to non-switch trials in the anterior cingulate cortex. To calculate neural activity associated with the conflict effect during the flanker task, the difference in neural activation was calculated during congruent and incongruent trials. Bilinguals activated bilaterally the anterior cingulate cortex, the left pre-supplementary motor area (BA 6), the left fusiform gyrus (BA 19/37), the left middle occipital gyrus (BA 19), the right precuneus (BA 7), the right fusiform gyrus (BA 37), and the right inferior and superior occipital gyri (BA 18 and 19). Monolinguals activated these same areas including the bilateral inferior superior parietal lobule (BA 7 and 40), the head of the caudate, and the right angular gyrus (BA 39).

A conjunction analysis was carried out to locate common patterns of neural activity seen during verbal and nonverbal tasks for each group. Bilingual activity associated with conflict conditions observed during both tasks was reported in the anterior cingulate cortex (BA 32) and pre-supplementary motor area (BA 6). Monolinguals revealed activity bilaterally in the anterior cingulate cortex (BA 32). The results from the fMRI analysis indicate that the anterior cingulate cortex works to resolve conflict across other cognitive domains as well as those specific to language processing. Activity within the anterior cingulate cortex was not exclusive to bilinguals; rather activation in the pre-supplementary motor area reported during verbal and nonverbal conflict tasks was exclusive in bilinguals. Luk and colleagues (2012) reported later that the pre-supplementary motor area is associated with bilinguals' language switching behavior, and these findings indicate that bilinguals further rely on this region when monitoring for conflict and inhibition in language and other cognitive domains.

This section summarizes a functional neuroimaging studies that assessed bilinguals' patterns of neural activation when executive functions are engaged during cognitive control and language control tasks. These studies reported an overlap with some of the predictions in Abutalebi and Green's (2008) model regarding bilingual language processing, and Luk et al.'s (2012) meta-analysis on bilinguals' language switching behavior. Luk et al. (2010) reported neural activation in bilinguals extending from cortical and subcortical regions associated with the bilingual language control network, and facilitated and effectively suppressed interference during response selection on a general cognitive task. Lastly, neural engagement during verbal and nonverbal conflict tasks was compared side-by-side in a conjunction analysis completed by Abutalebi and colleagues (2012). The areas active during both verbal and nonverbal conflict tasks were seen in the pre-supplementary motor area and the anterior cingulate cortex. Both regions are associated with the bilingual language control network (Abutalebi & Green, 2008; Luk et al., 2012), and engagement in this region in bilinguals was associated with smaller conflict effects as opposed to monolinguals.

1.4) Bilingualism influences neuroplasticity

There have been accounts regarding neuroplastic changes in the brain, i.e. changes in grey matter density or volume and white-matter connectivity due to environmental demands.

Maguire and colleagues (2000) found amongst taxi drivers significantly greater volumes of grey matter within the posterior hippocampi than in control subjects (i.e. not taxi drivers), a region associated with storing spatial representations necessary for navigation, and volume positively correlated with time spent being a taxi driver. Draganski and colleagues (2004) monitored participants who learned how to juggle over the course of three months, and observed and increase in grey matter volume in the bilateral mid-temporal area and left posterior intra-parietal sulcus, and a decrease in volume after participants stopped juggling for three months. Mechelli and colleagues (2004) reported greater density in grey matter within the left inferior parietal cortex in bilinguals, correlating with proficiency and inversely correlated with age of acquisition. The following section provides an account on the structural neuroimaging research that has investigated the influence of bilingualism on neuroplasticity of neural correlates involved in the execution of cognitive and language control processes.

The study reported in the previous section (1.3) conducted by Abutalebi and colleagues in 2011, included a VBM analysis to assess whether neural activation in the conflict effect region, anterior cingulate cortex, in bilinguals and monolinguals was associated with grey matter volume. Abutalebi and colleagues (2011) hypothesized that beneficial neuroplastic changes to the conflict effect region were influenced by bilingualism and associated with greater cognitive control. Abutalebi et al. (2011) supposed that bilinguals would be better adept to manage the general conflict effect. The same 17 high-proficient German-Italian female bilinguals (mean age=23.35, SD±4.59) and 14 Italian female monolinguals (mean age=26.55, SD±4.15) were assessed using the nonverbal task. The nonverbal task, flanker task (Eriksen & Eriksen, 19740) elicits a general conflict effect, the difference in functional activation and reaction times when subtracting congruent trials from incongruent trials. The task was administered over two sessions to test whether a reduction in the conflict effect (i.e. reduced reaction times, less activity in the region) would occur in the language groups.

The fMRI results revealed significantly more activity within the conflict effect region amongst monolinguals than bilinguals. The first session reported activity in the conflict effect region extending to a cluster of 77 voxels in bilinguals and a cluster of 289 voxels in monolinguals; group differences were not significant. The second session indicated a reduction in the conflict effect region to a cluster size of 10 voxels in bilinguals, and an increase in the region reflected by a cluster size of 397 voxels in monolinguals. Session two revealed that the magnitude of the conflict effect had increased in monolinguals, and decreased in bilinguals. In line with the predictions, bilinguals seem to be better adept at managing conflict indicated by the reduction in cluster size within the conflict effect region observed during session two.

The behavioral-structural analysis, revealed a positive correlation between grey matter volume of the anterior cingulate cortex and the behavioral results regarding the conflict effect. A regression analysis indicated that grey matter volume significantly predicted response differences concerning the conflict effect, revealing that greater grey matter volume in the anterior cingulate cortex was associated with smaller conflict effects. The functional-structural analysis revealed a positive correlation between grey matter volume and activity reported in the conflict effect region. A regression analysis indicated that grey matter volume within the region was a significant predictor of functional activity amongst bilinguals, but not in monolinguals. The structural analysis revealed that greater grey matter volume correlated with smaller conflict effects (i.e. smaller response differences), and greater grey matter volume amongst bilinguals positively correlated with activity observed in the conflict effect region. To summarize, the data suggests that greater grey matter volume in the anterior cingulate cortex amongst bilinguals is more effective at reducing conflict effects (i.e. smaller response differences), and more efficient, requiring less functional activation within the conflict effect region (i.e. smaller and reduced activity).

Zou, Ding, Abutalebi, Shu and Peng (2012) investigated the influence of bilingualism on neuroplasticity by carrying out a VBM and fMRI analysis assessing activation and grey matter volume in the head of the caudate nucleus. Zou and colleagues (2012) hypothesized that the executive demand for controlling two languages increases grey matter volume in the region associated with bilingual language control, the left caudate nucleus. Zou et al. (2012) predicted that differences in structural plasticity within the left caudate would correlate with functional activation within this region when comparing language switching conditions to non-switch conditions during a picture naming task switching paradigm. Participants included 14 late high-proficient Chinese L1 and Chinese sign L2 (normal-hearing) bimodal bilingual teachers of Chinese sign language (11 female, mean age=49, range=33-65), and 13 Chinese monolingual teachers (11 female, mean age=48, range=31-67).

Bimodal participants were used in the study to investigate whether patterns of functional activation matched those of unimodal bilinguals, and to isolate activity associated with language control salient from language modality. The 80 pictures selected for the study were controlled for signing, so that each picture would elicit as little arm and finger movement possible during scanning. The picture naming task language switching paradigm involved two experimental runs each, comprised of five baseline blocks (12 trials) and four experimental blocks (10 trials). No response was required for the baseline condition. For the non-switch condition, participants were asked to make overt responses and to name the picture in the L1, i.e. noun retrieval. For the switching condition, pictures were presented followed by a cue that displayed an icon for a 'mouth' (L1) or a 'thumbs-up' (L2) for 300ms, thereafter participants would respond or signal accordingly. Behavioral data was not collected during scanning, and monolingual participants did not partake in a switching paradigm (i.e. noun retrieval and verb generation).

The VBM results indicated bilinguals had significantly greater grey matter volume in the left caudate nucleus, the left inferior temporal gyrus, the bilateral superior frontal gyri, and the left amygdala than in monolinguals. The fMRI results indicated bilinguals had significantly more activity during the switching condition as oppose to the non-switch condition, areas included the left middle prefrontal cortex, and bilaterally in the anterior cingulate cortex, inferior parietal cortex, supramarginal gyri, pre/postcentral gyri, supramarginal lobule, and caudate nucleus. Functional activation in the left caudate during switching trials was significantly greater than during non-switching trials. Modalities (signing and speaking trials) during the switching condition were compared and no statistical differences in activity were found in the aforementioned regions. A functional-structural analysis revealed a positive correlation between grey matter volume in the left caudate and the magnitude of the switching effect, the difference in activity observed during switching and non-switch conditions. A regression analysis indicated grey matter volume in the left caudate of bilinguals was a significant predictor of activity associated with switching.

This section summarizes two neuroimaging studies that investigated the influence of bilingualism on neuroplasticity. Abutalebi and colleagues (2011) VBM findings revealed a relationship between grey matter volume and functional activation in the anterior cingulate cortex, the conflict effect region, in bilinguals. Zou and colleagues' (2012) similarly reported a relationship between volume and activation in the left caudate nucleus in bilinguals. Grey matter volume in the anterior cingulate cortex correlated with functional activation associated with the general conflict effect; whereas, grey matter volume in the left caudate correlated with functional activation observed during the language switching effect. Abutalebi et al. (2011) reported bilinguals had smaller conflict effects than monolinguals, and greater grey matter volume was associated with smaller conflict effects. Zou et al.'s (2012) findings also indicated bilinguals had greater grey matter volume in the left inferior temporal gyrus, the bilateral superior frontal gyri, and the left amygdala than in monolinguals.

1.5) Bilingualism influences cognitive function, despite ageing

This section continues to explore neuroimaging studies that assessed the influence of bilingualism on neuroplasticity. The following studies report on differences in neuroplasticity amongst bilingual and monolingual senior adults. These reports suggest that lifelong bilingualism may provide cognitive benefits, as proposed by Bialystok, Luk, and Craik (2012) and discussed earlier in section (1.1). These studies used structural neuroimaging data to investigate whether differences in brain plasticity may reflect a factor for protection against cognitive decline despite the degenerative effects of ageing.

Luk, Bialystok, Craik, and Grady in 2011, examined white matter integrity in senior bilingual and monolingual adults using a diffusion tensor imaging (DTI) technique. Luk and colleagues (2011) predicted that bilinguals would have better white matter integrity reflected by a more widely distributed network associated with bilingual language control, and would have greater connectivity to help better facilitate and transfer information during cognitive processing. Luk et al. (2011) hypothesized that bilinguals would exhibit greater integrity in white matter tracts extending between regions reflected by higher values of fractional anisotropy, especially in the corpus callosum. White matter integrity is determined by the level of fractional anisotropy indicated by the degree and the direction of water diffusion in white matter tracts. Types of diffusion include axial diffusivity, diffusion extending parallel to white matter tracts, and radial diffusivity, diffusion extending perpendicular to white matter tracts. Radial diffusivity is reported to be a marker for the degenerative effects of ageing (Madden et al., 2009). Luk et al. (2011) predicted bilinguals would have lower radial diffusivity in those regions that reflect greater fractional anisotropy compared to monolinguals.

The researchers collected DTI data by conducting a resting-state functional analysis in order to identify regions that reflected salient differences in connectivity and fractional anisotropy, independent of task effects. A total of 28 right-handed healthy older adults participated in the study (mean age=70.5, SD=3) consisting of 13 older lifelong bilinguals (8 female), who spoke English L1 and the L2 (alphabetic) after age 11, and 13 English-speaking monolinguals (7 female). Both groups were matched on age and gender, and had comparable socioeconomic backgrounds. Participants completed a battery of neuropsychological tests that included the MMSE, Shipley Institute of Living Scale – vocabulary test, verbal fluency, design fluency- Kaplan Executive Functions System, Stroop task, and the Trail-making task. Performance was comparable between groups, but no further figures were reported.

Bilinguals exhibited better integrity reflected by higher values of fractional anisotropy than monolinguals. Greater fractional anisotropy was reported in the corpus callosum, extending posteriorly to the bilateral superior longitudinal fasciculi and anteriorly to the right inferior frontal-occipital fasciculi and uncinate fasciculus. As predicted, monolinguals had higher values of radial diffusivity within the corpus callosum. To assess whether greater integrity correlated with greater connectivity between more widespread regions associated with the bilingual language control network, the connectivity extending from the bilateral inferior frontal gyri was assessed. This region is strongly associated with cognitive and language control (Mechelli et al., 2004; Abutalebi et al., 2008; Luk et al., 2010). Bilinguals revealed greater fractional anisotropy in the right inferior frontal gyrus and the corpus callosum connecting the frontal lobes. Bilinguals revealed greater connectivity extending from the inferior frontal gyrus to the bilateral middle temporal gyri, right inferior parietal lobule, the precuneus, bilateral occipital gyri, and left caudate. Monolinguals had more intrafrontal connectivity. These findings reveal bilinguals had better white matter integrity and connectivity extending from the corpus callosum and distributed across the network associated with bilingual language control. Monolinguals exhibited a more confined network of connectivity, and exhibited more radial diffusivity associated with ageing. The neuropsychological results were "comparable" between groups and go further unreported; therefore, no interpretations can be made as to whether greater integrity and connectivity in bilinguals is associated with greater executive function or cognitive benefits against ageing.

Gold, Johnson and Powell (2013) conducted a DTI and VBM analysis to measure white matter integrity (i.e. levels of fractional anisotropy and radial diffusivity) and grey matter volume in senior bilinguals and monolinguals. The study investigated whether lifelong bilingualism may provide a cognitive reserve and act toward retaining cognitive function despite age-related neurodegeneration (i.e. atrophy). The cognitive reserve hypothesis (Stern, 2009) proposes that individuals with greater neurocognitive reserve may function normally despite greater degrees of ageing effects and/or pathology. A group of 20 senior healthy lifelong bilinguals (10 female, mean age=63.9, SD=4), who spoke English L1 and the L2 before age 11, participated in the study. A group of 20 healthy English-speaking monolinguals (10 female, mean age=64.4, SD=5.1) were matched and selected to participate. The 40 participants completed a battery of neuropsychological tests that included the MMSE, the Peabody Picture vocabulary test, the Cattell Culture Fair Intelligence Test, the Wechsler Memory Scale Digit Span, Spatial span, and logical memory subtests, and a color-shape task switching paradigm. Both groups scored equally on all tests with the exception of the task-switching paradigm. Senior bilinguals had significantly smaller switch costs, the mean difference in reaction times between switch and non-switch trials, than monolingual peers. The study does not further discuss switch cost differences.

The data revealed older bilinguals had lower levels of fractional anisotropy in the inferior longitudinal fasciculus and inferior fronto-occipitol fasciculus, the fornix, and the corpus callosum. The aforementioned regions form part of the memory circuit, and atrophy in these areas are associated with the onset of Alzheimer’s disease (AD, Stebbins & Murphy, 2009). Additionally, the bilingual group showed several regions with higher values of radial diffusivity, the majority of which overlapped in regions that exhibited lower levels of fractional anisotropy, the inferior fronto-occipital fasciculus and the corpus callosum. The monolinguals did not exhibit any regions with lower levels of fractional anisotropy or higher values of radial diffusivity, indicating better white matter integrity than bilinguals. The VBM analysis did not return any statistically significant differences in grey matter volume between the two groups.

In summary, the DTI findings reported by Luk, Bialystok, Craik, and Grady (2011) revealed senior bilinguals had greater white matter integrity and more widespread connectivity in regions associated with the bilingual language control network than monolinguals. Behavioral figures were not reported; consequently, no interpretations can be made whether greater integrity and connectivity correlated with greater executive function. The DTI findings reported by Gold, Johnson and Powell (2013) revealed senior bilinguals had poorer white matter integrity than monolingual peers in similar regions reported by Luk et al. (2011), the fronto-occipitol regions and the corpus callosum. In Gold et al.'s (2013) study, senior monolinguals and bilinguals were matched and exhibited equal levels of cognitive function; however, bilinguals outperformed monolinguals during the perceptual task switching paradigm, but these findings go undiscussed. Gold, Johnson and Powell's (2013) study indicated that despite the degenerative effects of ageing, senior bilinguals functioned at normal to greater cognitive levels than monolinguals. This suggests lifelong bilinguals may be exhibiting a degree of cognitive reserve (Stern, 2009). On the other hand, Gold, Johnson and Powell (2013) propose that senior bilinguals may perhaps rely on neural compensation (Stern, 2009) by outsourcing alternative neural correlates to execute cognitive processing that should otherwise be disrupted by neural degeneration.

2) Current study – Hypotheses

The literature indicates that bilingual language control exercises executive functions to better manage the facilitation and suppression of interference while selecting and inhibiting responses. These executive functions are not limited to the domains of language but carry over into other cognitive domains in children, adults, and senior adults. Bilinguals are therefore reported to outperform monolingual peers during cognitive tasks that require a degree of conflict monitoring and inhibition, and exhibit patterns of activation associated with bilingual language control processes (Bialystok et al., 2006; 2009; Luk et al., 2010; Abutalebi et al., 2011; Zou et al., 2012). These cognitive advantages have been reported to influence neuroplasticity (Mechelli et al., 2004, Abutalebi et al., 2011; Zou et al., 2012). If older bilinguals exhibit better cognitive performance (Bialystok et al., 2006; Gold et al., 2013), would performance correlate with differences in neuroplasticity relative to regions in the bilingual neurocognitive network?

The present study investigates the influence of bilingualism on cognitive performance in relation to neuroplasticity in senior bilingual adults. The first aim tests whether lifelong bilingualism influences the asymmetry of the bilateral caudate nucleus. Each caudate is comprised of a head, body, and tail that form a c-shaped arched mass of dopaminergic neurons, see Appendix, Figure (1). The caudate nucleus and the putamen form the striatum, where input information is conveyed by the cerebral cortex and output is sent to the other nuclei of the basal ganglia circuitry, the globus pallidus and substantia nigra (Abutalebi et al., 2013a). These structures communicate with the subcortical structure, the thalamus, which acts as the "gate" to the cortex where information is looped back and returned to (Leh et al., 2007). It was hypothesized that lifelong bilingualism would influence grey matter volume in the left caudate. Bilinguals were predicted to exhibit a leftward asymmetry in the bilateral caudate. A leftward asymmetry is indicated by a larger left caudate as opposed to the right, reflecting the demand of processing two languages in the language dominant (left) hemisphere (Zou et al., 2012).

The second aim of the experiment was to test senior bilingual and monolingual adults on their cognitive performance. It was further hypothesized that leftward asymmetry in the bilateral caudate would correlate with task performance amongst senior bilinguals. Bilinguals were predicted to exhibit better performance during the flanker task. Abutalebi et al. (2012) revealed bilinguals exhibited greater-grey matter volume in correlation with reduced (conflict effect) response costs. Will lifelong bilinguals also exhibit a relationship between grey matter volume in the caudate nucleus and task performance? The present study further investigates the influence of L2 proficiency and socio-economic status on grey matter volume in the bilateral caudate and task performance.

3) Methods

3.1) Participants

This study was granted approval by the Human Research Ethics Committee at the University of Hong Kong. Written informed consent was obtained from all participants who were paid $150 HK dollars plus a transportation allowance. A total of 30 healthy senior bilingual subjects between the ages of 55 and 75 years from Hong Kong participated in the study (17 Female; 63.2 Mean Age, SD=5.86). 16 participants spoke Cantonese L1 and learned English L2 at a mean age of 10.69 (SD=9.6). The 14 remaining participants spoke Mandarin and Cantonese; 10 subjects spoke Mandarin L1, and four spoke Cantonese L1. Mandarin and Cantonese speakers learned the L2 at a mean age of 21.08 (SD=13.29). A total of 30 healthy Italian subjects between the ages of 49 and 75 years from Milan, Italy, were selected as the control group (16 Females; 61.85 Mean Age, SD=6.71). All monolingual subjects had little to no exposure to a foreign language.

Participants with a history of neurological or psychiatric illnesses, scored 24[4] or lower on the Mini-Mental State Examination (MMSE), and those who scored less than 50% cumulatively on both L2 proficiency tasks were excluded. A total of 4 bilingual subjects were therefore excluded from the study due to low scores on the MMSE and proficiency tests. The analysis to be

[4] MMSE, introduced by Folstein in 1975, it is a test that measures cognitive impairment. Scoring below 9 points indicates severe impairment, typically reflective of Alzheimer's disease and dementia. Scoring between 10 and 18 points indicates moderate cognitive impairment. Scoring between 19 and 24 points indicates mild cognitive impairment. It has been suggested that scores are influenced by level of education; and therefore should always be considered (Mungas, 1991; Crum et al., 1993).

reported was performed on 26 of the 30 senior bilingual subjects (16 Female; 62.65 Mean age, SD=5.91), 13 subjects in the Cantonese-English group, and 13 subjects in the Mandarin-Cantonese group. All monolingual subjects were included in the analysis.

Bilingual and monolingual participants matched in age, gender, education and MMSE scores, see Table (1). The mean age of the bilingual group was 62.65 years old (SD=5.92), and the mean age of monolingual group was 61.85 years old (SD=6.71), *p*=.639. The mean for years of formal education regarding bilinguals was 13.02 (SD=4.16), and the mean for monolinguals was 12.33 years (SD=4.54), *p*=.561. The mean score on the MMSE for bilinguals was 28.27 (SD=1.49), and monolinguals had a mean score of 28.50 (SD=1.36), *p*=.546. Lastly, the gender ratio in bilinguals (16:10 females) and monolinguals (16:14 females) was not significant, *p*=.545. In summary, there were no statistically reliable differences in age, years of formal education, MMSE scores, and gender ratio between bilinguals and monolinguals.

TABLE 1.	Demographic Results		
	Bilingual (26)	Monolingual (30)	P-values
Age	62.65 (5.92)	61.85 (671)	*p*=.64
Gender (F/M)	16/10	16/14	*p*=.55
Education	13.02 (4.16)	12.33 (4.54)	*p*=.56
MMSE	28.27 (1.49)	28.50 (1.36)	*p*=.55

3.2) Behavioral Assessment

All bilingual participants completed a language background questionnaire, and provided information regarding their L1 and L2 (i.e. language from birth, age to acquire or learn the L2, and language dominance). In terms of measuring the degree of L1 and L2 exposure, bilinguals estimated the average hourly amount they came into contact with an L1-speaking environment and an L2-speaking environment. Participants were asked to carefully consider and to account for the wide range of activities they encounter on an average day, such as speaking with colleagues, friends and family, watching television, listening to radio, reading, writing, etc.

Participants were also asked to fill out a detailed questionnaire concerning their socio-economic status. The questionnaire was available from the MacArthur Foundation Network (SES, http://www.macses.ucsf.edu/research/socialenviron/sociodemographic.php). Each participant provided information regarding (1) their degree or level of education based on the number of years of formal education, (2) both their personal and total family household income based over the most recent 12-month period, and (3) a personal account of one's self-perceived social position relevant to her or his local community and country. Raw scores for education, income, and social positions were standardized into Z-scores and compiled for a composite score.

Fifteen of the 30 monolinguals selected for the study had filled out the SES questionnaire, providing information regarding their level of education, income, and social position. Similarly, all three raw scores were standardized in order to calculate the Z-scores, and a composite SES Z-score was further calculated.

3.3) Language Task

To assess language proficiency, bilingual participants completed a picture naming task in both their L1 and their L2. Pictures were line drawings depicted in a red or green color to indicate which language the picture was to be named. A total of 30 picture stimuli were used for each language. Pictures were chosen based on their level of familiarity and visual complexity, and taken from Snodgrass and Vanderwart's picture set (Snodgrass & Vanderwart, 1980). Monolingual speakers completed a separate set of pictures to test L1, comprised of 30 picture stimuli to be answered in Italian (See Appendix). Bilinguals were also asked to take part in an oral translation task (Perani et al., 1998, Abutalebi et al., 2011), as an added measure to check proficiency. Bilingual participants were asked to translate from the L1 to the L2 on a total of 66 lexical items, i.e. nouns. Items were split into a high, medium, and low frequency L1 word lists, each list containing 22 word stimuli (See Appendix).

Each participant was scored for accuracy out of 30 for each of the L1 and L2 naming tasks, and accuracy out of 66 on the translation task. Lastly the L2 naming and translation scores were compiled for a composite L2 proficiency score. Monolinguals selected for the study scored at ceiling levels during L1 naming, with a mean L1 score of 29.73 or 99.1% (SD=.46). Bilinguals yielded a mean score of 23.69 or 79.0% on L1 naming (SD=.12), a mean score of 19.16 or 63.9% on L2 naming (SD=.13), and a mean score of 32.15 or 53.6% on translations (SD=.10). Furthermore, the compiled L2 proficiency score yielded a mean score of 58.7% (SD=.59). One subject scored a 27% on L2 naming and 16% on translation, scoring a composite L2 score of 22% and was therefore excluded from the study. Overall, all bilingual participants who were included in the study had an intermediate or high level of L2 proficiency.

3.4) Flanker Task

The Attention Network Test (ANT) Flanker task (Fan et al., 2002; Rueda et al., 2004) is comprised of congruent stimuli, target (central) arrows flanked by arrows pointing in the same direction (e.g. → → → → →); incongruent stimuli, target arrows flanked by arrows in the opposite direction (e.g. → → ← → →); and neutral stimuli, target arrows flanked by lines (e.g. -- -- → -- --). Incongruent stimuli call upon executive functions that facilitate or suppress interference to resolve conflict while selecting and inhibiting responses, when the target arrow is flanked by distractor flanking arrows pointing in the other direction. Participants must select the appropriate response, matching the direction of the target arrow, while inhibiting the alternative response caused by opposing flanking arrows. Incongruent conditions are therefore expected to exhibit poorer (i.e. slower) reaction times, reflecting the processing time needed to resolve the conflict. Congruent conditions are presented to serve as a point of comparison to incongruent conditions and facilitate the selection of responses. The neutral conditions serve as a baseline during the experiment where neither functions for facilitation nor inhibition are engaged. Subjects were asked to respond as quickly and accurately as possible by pressing the

left or right button on a response pad in accordance with the target arrow. Subjects faced a computer screen where stimuli were presented. There were two separate experimental runs presented in random order, 96 trials per run, containing 32 trials for each of the 3 flanking conditions. Each trial was preceded by one of four visual cues: a double cue, a fixation cross with both an asterisk on either side of the cross [* + *]; a central cue, an asterisk placed in the center of the screen [*]; a spatial cue, with an asterisk placed above the fixation cross [+]; and
*
no-cue, simply a fixation cross in the center of the screen [+]. Visual cues controlled for alerting effects that occur when subjects anticipate the trial that follows (Costa et al., 2008). Each cue appeared 8 times per condition. A fixation cross was present on the screen throughout the entire experiment except during central cues preceding trials. Subjects were recorded on accuracy for each trail. Individual reaction times (RTs) were tallied for each condition during each experimental run allotting a total of 6 RTs recorded per subject (i.e. Ex.1-Congruent RTs, Ex. 2-Congruent RTs, Ex.1-Incongruents RTs…Ex.2-Neutral RTs).

3.5) VBM Analysis

Images for bilingual subjects were obtained with a 3T Achieva Philips MR Scanner (Philips Medical Systems, Best, NL) at the 3T MRI Center at the University of Hong Kong. Images for monolingual subjects were obtained with the same model scanner, 3T Achieva Philips MR Scanner (Philips Medical Systems, Best, NL) located at the CERMAC Center at San Raffaele University in Milan, Italy. Axial high-resolution T1 structural MR scans were collected for all subjects using the following image parameters: magnetization prepared rapid gradient echo, 150 slice T1-weighted image, TR = 8.03ms, TE= 4.1ms; flip angle = 8°, FOV = 250x250, matrix = 256, TA = 9.35 min, mode = 3D FFE, sense factor = 1, NSA = 1, resolution = 1x1x1.

Preprocessing procedures for the bilingual subjects included: (1) visual inspection and manual orientation of natural (raw) MR images; (2) segmentation of images using VBM8 (voxel-based morphometry) toolbox extensions in accordance with structural algorithms attained through SPM5 (spatial parametric mapping; http://www.fil.ion.ucl.ac.uk/spm/software/spm8/) in MATLAB Version 8.0 (Matrix Laboratory Computer Programming Language and Environment, http://www.mathworks.nl/products/matlab/); (3) creation of a whole-brain DARTEL template using SPM5 DARTEL toolbox; 4) normalization of images to MNI (Montreal Neurological Institute) space using whole-brain DARTEL template (MNI, http://www.bic.mni.mcgill.ca/ServicesAtlases/ICBM152NLin2009); (4) smoothing normalized images with Gaussian Kernel.

A visual inspection of MR images was conducted to confront any field distortions and movement artifacts. All scans were thereafter realigned manually one-by-one, reorienting the origin to align with the anterior and posterior commissure (AC/PC line[5]). Typically following reorientation, MR images are run through an automated MATLAB script to align with default GM tissue probability maps (TPM); however, following this procedure would result in distorting the data obtained from sample images because default settings are matched to younger and healthier populations. Therefore aligning the data with default TPMs was not carried out. Rather, using structural algorithms obtained in the SPM5 toolbox, reoriented MR images were segmented into grey matter (GM: 1), white matter (WM: 2), and cerebrospinal fluid (CSF: 3) registered in native (C) space images and DARTEL (RC) images within MATLAB 8.0. Native space images show the reoriented and corrected dimensions of the image pertaining to each subject's brain size. DARTEL images exhibit the reoriented and corrected dimensions pertaining to each subject while aligning GM, WM, and CSF between subjects. DARTEL images are slightly distorted to create a whole-brain template that represents the sample average.

Once all images were segmented, they were run through a spatially adaptive nonlocal means filter (Manjon et al., 2010) using the Markov random field approach to remove any

[5] AC/PC line is the meeting of two fiduciary points, one point extending from the anterior commissure and the other extending from the posterior commissure.

artifacts resulting from the segmentation process, e.g. along the edges of the scan. Thereafter, a whole-brain DARTEL template based on all subjects is created using the filtered reoriented natural image, filtered native space images (C1, C2, C3) and filtered DARTEL images (RC1, RC2, RC3) within an unrestricted open space. The DARTEL toolbox adjusts each image to provide sharper localizations of GM, WM, and CSF by aligning all tissues within and between subjects, averaging those localizations to create a more precise whole-brain template relative to the current sample. The whole-brain DARTEL template structurally accounts for the influence of age, i.e. atrophy.

The filtered natural image, native images, and DARTEL images must then be spatially normalized to MNI space so that voxels are stretched and compressed to account for folding and/or cortical thickness. The DARTEL template is included in the normalization process and is registered to MNI space, providing an underlying shape for the final image deformations. Consequently, the images become slightly warped or enlarged after normalization to account for the GM and WM that is otherwise lost between voxels. The last step of the preprocessing procedure is smoothing normalized images to obtain a normal distribution of GM volume within and between subjects. The smoothing process helps account for eccentricities such as volumetric differences that show folding or thickness avoiding the misclassification of voxel parameters that would otherwise be labeled as artifacts. Images are smoothed using a smoothing kernel, the Gaussian function. The Gaussian Kernel is set to the following function 8mm full-width at half-maximum (FWHM) to allow for “blurring” or smoothing amongst the voxels, with a voxel size of 1.5mm. The smoothed images underwent a “concentration” analysis, which provides the amount of grey matter per unit of intracranial volume. This is a function that divides the grey matter volume by the total intracranial volume (TIV) to correct for variations in head size; thus, compensating for the difference in skull and brain size between the bilingual Asian participants (smaller) and the monolingual Caucasian participants (larger). The resulting images represent regional volumes of tissue, displaying regional concentrations of grey and white matter relative to the pre-processed data, and is used for the statistical analysis.

Lastly, to extract GM volumes (GMV, in cm^3) and normalized mappings for the two ROIs, the left caudate and right caudate nucleus, these regions were given a binary mask image, coregistered and resliced independently for the bilingual and monolingual group. Masks were based on Automatic Anatomical labels (AAL, Tzourio-Mazoyer et al., 2002) in the EasyVolume toolbox provided in SPM5 (Maldjan et al., 2003; Maldjan et al., 2004).

3.6) Statistical Analysis

To test the hypothesis that lifelong bilingualism influences GMV in the bilateral caudate, paired samples t-test was run to test whether GMV in left caudate was greater than the right between and within groups. The index of hemispheric asymmetry was calculated to measure asymmetry of the bilateral caudate within groups. The paired t-test was then followed by an ANOVA to assess whether behavioral differences (i.e. age, gender, years of education, and MMSE) were associated with the variance in GMV observed in the left and/or right caudate in each group.

To test the hypothesis that leftward asymmetry correlated with bilingual performance, ANOVAs were run to examine main effects and interactions associated with the outcome of accuracy during the Flanker task. Specifically main effects and interactions concerning language group, condition type, and experimental run were assessed. A multilevel analysis was carried out to assess whether GMV within the left and/or right caudate predicted the dependent variable, percent accuracy during incongruent and during congruent conditions. A post hoc analysis was completed on each language group to assess whether GMV in each caudate was predictive of accuracy for incongruent and congruent conditions.

To further test the second hypothesis that GMV correlates with cognitive performance, reaction times (RTs) were assessed. The log RTs pertaining to each condition per trial (i.e. 6 RTs per individual) was analyzed for a more normalized distribution. An ANOVA tested whether main effects and interactions concerning language group, condition type, experimental run were associated with log RTs. A multilevel analysis was completed on the dependent variable, log RTs (6 RTs per subject), to test whether GMV in the LC and RC were predictive of group performance (RTs) across condition types and experimental runs. A post hoc analysis was completed on each language group to assess whether GMV in each caudate was predictive of log RTs for incongruent and congruent conditions.

An ANOVA was carried out to test whether SES factors were associated with GMV for each caudate for the bilingual groups (i.e. Cantonese-English and Mandarin-Cantonese), and the monolingual group. Thereafter a partial correlation was run, controlling for total intracranial volume (TIV) between the bilingual and monolingual group, to investigate whether hidden relationships between SES and asymmetry existed. After which, stepwise regression analyses were carried out to further examine if SES variables were in fact reliable predictors for GMV found in each caudate amongst each of the groups.

An ANOVA was run to test for differences in performance on L1, L2 naming, translating, and age of acquisition (AoA) were present between the bilingual groups, Mandarin-English speakers (n=13) and Cantonese-English speakers (n=13). Furthermore, a regression analysis was carried out to test whether naming performance and AoA were predictors of GMV observed in the left and right caudate within and between groups.

4) Results

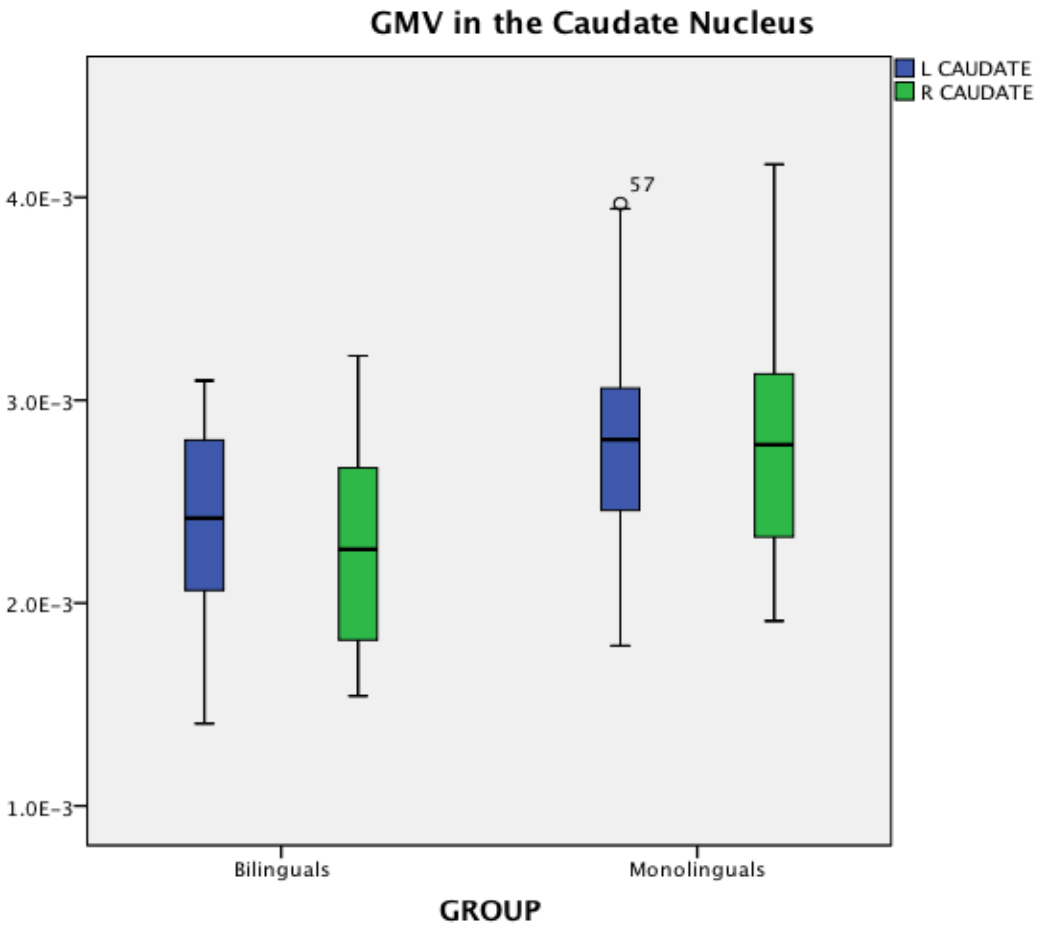
4.1) VBM Results

It was hypothesized that bilingualism influences GMV of the bilateral caudate, and predicted that bilinguals would exhibit leftward asymmetry, where the left caudate would exhibit greater GMV than the right caudate. The figures for the mean and standard deviations of GMV in each caudate and TIV are shown in Table (2), and Figure (1). Monolinguals have greater TIV, and therefore exhibit greater GMV in each caudate with little difference between the left and right caudate volume. Bilingual subjects exhibit greater GMV in the left caudate than the right caudate; see Appendix for Figure (1.a).

TABLE 2.	Grey Matter Volume in cm3		
Groups	Left Caudate	Right Caudate	TIV
Bilingual (26)	.002431 (.000461)	.002291 (.000492)	1007.843 (87.495)
Monolingual (30)	.002772 (.000523)	.002785 (.000566)	1104.931 (122.480)

* TIV: total intracranial volume

Figure 1) Boxplot, Average Grey Matter Volume in each Caudate per Language Group



A paired-sample t-test assessed whether GMV in the LC to that of the RC within each group was significantly different. The difference between the LC and RC in bilinguals was significant, $p<.05$, and was insignificant in monolinguals, $p=.844$. The index of hemispheric asymmetry was computed as the absolute percentage difference, 100% * [(left – right) / .5 (left + right)], and the left to right asymmetry was 5.93% amongst bilinguals, and -0.468% amongst monolinguals (formula obtained from Gunning-Dixion et al., 1998). In summary, bilinguals exhibited greater GMV in the left caudate and leftward asymmetry was statistically significant.

An ANOVA was used to assess whether GMV in the left or right caudate was influenced by demographic variables. An ANOVA with GMV in the LC as the dependent variable was run to test for main effects and interactions for the following variables: group, gender, MMSE, education, and age. An ANOVA was similarly run where the dependent variable was GMV found in the RC, using the same behavioral variables to test for main effects and interactions. For the ANOVA run on the LC, main effects returned for TIV accordingly, $F(1,49)=32.46$, $n^2=.398$, $p<.001$; and for age, $F(1,49)=8.20$, $n^2=.143$, $p<.01$, $R^2=.610$. The ANOVA run on the RC, similarly returned main effects for TIV, $F(1, 49)=14.37$, $n^2=.227$, $p <.001$; and age $F(1,94)=5.01$, $n^2=.092$, $p<.05$, $R^2=.545$. Hereafter, regression analyses were carried out to test whether age was predicative of each dependent variable, GMV found in the left and right caudate. The regression model for GMV in the LC returned age as a predictor for all participants, $F(1,54)=4.38$, $p<.05$, with an effect size (R^2) of 0.075, see Appendix, Figure (1.b). A regression was similarly run on the right caudate amongst both groups, but the variable of age did not return as relevant predictor. A post hoc analysis was run on each language group and age was no longer a predictor of GMV in the LC or the RC ($p >.05$).

4.2) Flanker Results

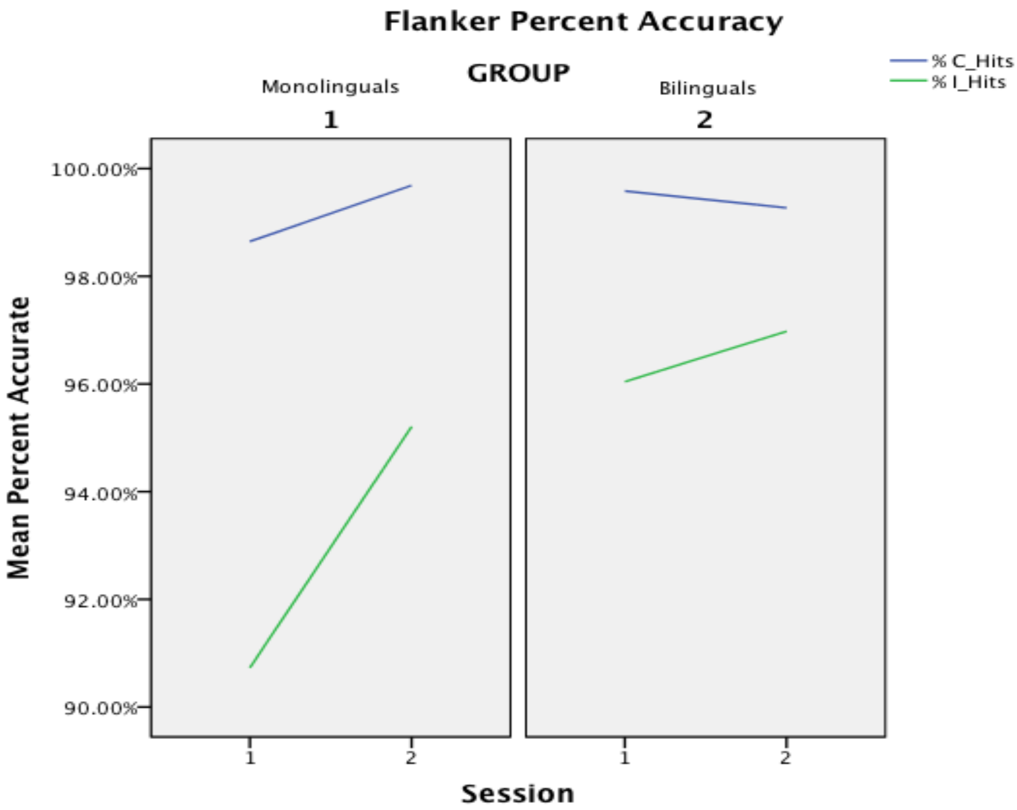
To test the hypothesis that leftward asymmetry in bilinguals would correlate with cognitive performance, bilinguals and monolinguals were assessed for accuracy and reaction times (RTs) on the ANT Flanker task. Bilinguals were assumed to perform more accurately and/or have shorter RTs than their monolingual peers. The question was whether bilingual performance was associated with leftward asymmetry in the caudate nucleus of bilinguals?

Accuracy

Bilingual performance varied little from monolinguals. The bilinguals outscored across all conditions during the first experimental run, and on all but the congruent condition during the second run, see Table (3) and Figure (2). An ANOVA tested whether main effects and interactions for group, experimental condition, and experimental run were associated with total percent accuracy. No main effects were found. An ANOVA was run to assess whether GMV in each caudate was influenced by accuracy. The analysis for GMV in the LC indicated a significant interaction between group and congruent conditions, $F(2,47)=5.527$, $n^2=190$, $p<.01$; between group and incongruent conditions, $F(2,47)=.\ 5.354$, $n^2=.186$, $p<.01$; between group and the first run, $F(2,47)=5.260$, $n^2=.183$, $p<.01$; and between group and the second run, $F(2,47)=5.637$, $n^2=.193$, $p<.01$; effect size (R^2) .298.

TABLE 3.	Accuracy - Mean Percent					
Group	Incongruent Total %	Congruent Total %	1st Run		2nd run	
			Inc. %	Con. %	Inc. %	Con. %
Bilingual	96.63 (6.81)	99.33 (1.60)	96.27 (6.00)	99.51 (1.15)	97.00 (8.77)	99.16 (3.13)
Monolingual	92.96 (15.61)	99.17 (2.16)	90.73 (21.41)	98.65 (3.73)	95.21 (13.48)	99.69 (0.95)

Figure 2.) Flanker- Accuracy



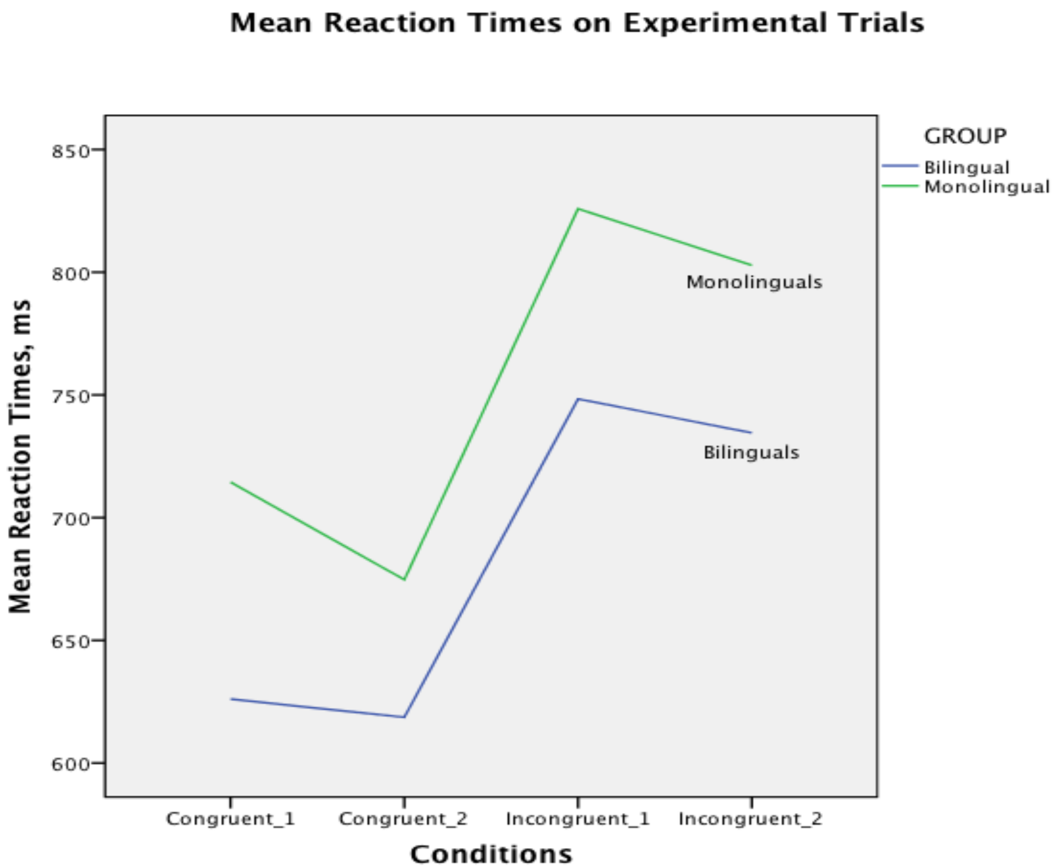
Post hoc two-level mixed analysis was run to test whether the relationship between accuracy and GMV of the left caudate was relevant for language groups independently. The grey matter volumes of the left and right caudate were entered as the dependent variables. Fixed effects included variables pertaining to the percent accurate during congruent conditions; incongruent conditions; run 1 and run 2. The model exclusive to bilinguals showed a positive correlation between GMV in the left caudate and performance accuracy. GMV in the left caudate of bilinguals was significantly predicted by accuracy during congruent conditions, $F(1,26)=8.51$, $t(-2.917)$, $p<.01$; incongruent conditions, $F(1,26)=5.32$, $t(2.306)$, $p<.05$; experimental run 1, $F(1,26)=6.19$, $t(2.488)$, $p<.05$; and experimental run 2, $F(1,26)=5.48$, $t(-2.341)$, $p<.05$.

Reaction Times

The figures regarding mean reaction times (RTs) and standard deviations on congruent and incongruent conditions during the first and second experimental run between the two language groups are shown below in Table (4). Figure (3) depicts how bilinguals had overall shorter RTs than monolinguals and how RTs decreased over time and varied between each condition. Bilinguals had significantly shorter RTs across all conditions, $p<.05$, see Appendix for Table (1.c). The conflict effect (incongruent mean RTs – congruent mean RTs) was calculated across sessions and in total for each group. Bilinguals did exhibit smaller conflict effects with a reduction in the second session. The difference between language groups was marginally significant between groups during session 2, $p=.093$. An ANOVA was run to test whether main effects and interactions for group, condition type, and experimental run were associated with RTs. The log (*ln*) of individual RTs pertaining to all three conditions from both runs was input as the dependent variable (i.e. six RTs), to control for a more normal distribution. The analysis returned main effects for group, $F(1,329)=35.97$, $n^2=.099$, $p<.001$; and for condition, $F(5, 329)=15.31$, $n^2=.189$, $p<.001$, and $R^2=.255$.

TABLE 4.	Reaction Time Means in ms						
Group	1st Run		2nd Run		Conflict Effect		
	Inc.	Con.	Inc.	Con.	S1	S 2	Total
Bilingual	730.51 (77.47)	618.31 (68.76)	713.69 (75.55)	607.68 (65.76)	112.21 (50.99)	106.01 (32.60)	218.21 (72.24)
Monolingual	825.87 (198.33)	714.47 (136.56)	802.81 (170.49)	674.71 (125.94)	111.40 (148.27)	128.10 (58.47)	239.50 (163.01)

Figure 3.) Flanker – Reaction Times



A multilevel analysis tested whether the log RTs was predicted by GMV found in the left and/or right caudate. The two-level analyses included fixed variables: the intercept, group and GMV in the left caudate, and group and GMV in the RC. The intercept was input to control for random variables. The interaction between group and GMV in the LC figures was predictive of RTs, $F(2,56)=4.767$, $p<.05$. A post hoc analysis revealed that GMV in the LC correlated with log RTs only in the bilingual group, $F(1,26)=8.766$, $b=-162.78$, $t(-2.961)$, $p<.01$.

Another multilevel analysis tested whether GMV in each caudate was predicted by congruent log RTs and/or incongruent log RTs. The fixed effects included the intercept, group and GMV in the LC, group and GMV in the RC. The random effect included the intercept. A marginally significant interaction was found between group and GMV in the LC regarding incongruent log RTs, $F(2,56)=2.982$, $p=.059$. Significant interactions were found between group and GMV in the LC, $F(2,56)=5.496$, $p<.01$, and GMV in the RC, $F(2,56)=4.269$, $p<.05$ regarding congruent log RTs. A post hoc analysis was carried for each group. Amongst bilinguals, the GMV in the LC returned as a significant predictor for both incongruent log RTs, $F(1,26)=6.125$, $b=-135.85$, $t(-2.475)$, $p<.05$, and congruent log RTs, $F(1,26)=9.691$, $b=-187.01$, $t(-3.113)$, $p<.01$. GMV in the RC did not significantly predict the variability in log RT for either condition amongst bilinguals, $p>.05$. The same post hoc analysis was completed for the monolingual group but neither GMV in the LC nor the RC was statistically relevant in determining RTs across conditions.

The results from the analysis thus far have indicated bilinguals exhibit leftward asymmetry within the bilateral caudate, where GMV in the LC is significantly greater than within the RC. The results further indicate that bilinguals outperform on the Flanker task compared to their monolingual peers, yielding overall greater accuracy and shorter RTs. Furthermore, greater accuracy across all conditions and during both experimental conditions correlated with greater grey matter volume found in the left caudate of bilinguals. Lastly, grey matter volume in the left caudate of bilinguals was inversely correlated with log RTs, and was inversely correlated with log RTs during both congruent and incongruent conditions types. Leftward asymmetry was predicted by better accuracy and left caudate volume predicted faster RTs in senior bilinguals.

4.3) SES Results

An analysis investigated whether GMV found in the LC and/or RC was associated with factors of socio-economic status: income, education, social position, and the composite SES score. A Bonferroni correction analysis tested for group differences across SES variables, see Appendix for Figure (1.c). No differences were found. An ANOVA was run on each caudate that included all the behavioral variables, and each SES Z-score. None of the SES factors yielded any statistical relevance. A partial correlation to control for differences in TIV amongst subjects was run to investigate if SES factors correlated with GMV in the LC and/or RC. No relationships were observed with regard to the RC. The analysis indicated greater GMV in the LC inversely correlated with SES scores for social position (R=-0.351, p<.05), education (R=-0.369, p<.05), and composite scores (R=-0.417, p<.01).

A regression analysis was run on GMV in the LC, all four SES factors were entered into the model including TIV, as it is the strongest predictor of GMV. In accordance with results obtained from the ANOVA, none of the SES factors were significantly relevant in predicting GMV in the LC. A post hoc analysis was carried out separately for each group to test whether SES was associated with GMV in the LC. TIV was entered first and all SES variables were entered stepwise in the following block so that the most statistically relevant SES factor(s) would return. The Cantonese-English bilingual group returned statistically relevant figures. Two models were run in the regression. Model 1 was significant and included only TIV, p<.05, and Model 2 was significant containing TIV and the composite Z-score, $F(2,10)$=8.64, R^2=.633, p<.01; TIV, B=.655, $t(3.387)$, p<.01; composite Z-score, B=-.553, $t(-2.860)$, p<.05). In summary, an inverse relationship was observed between the composite SES score and GMV found in the LC amongst Cantonese-English bilinguals.

4.4) Proficiency Results

An analysis investigated whether L1/L2 proficiency and age of acquisition (AoA) differed amongst bilinguals, the Cantonese-English speakers and Cantonese-Mandarin speakers, and whether such differences influenced the variance seen in GMV within each caudate. An ANOVA tested for group differences in L1 naming, L2 naming, translating, and AoA. The analysis returned a significant differences for L1 naming, $F(1,24)$=9.641, p<.01 and for AoA, $F(1,24)$=5.209, p<.05, but no group differences for L2 naming or translating. Cantonese-English bilinguals performed more accurately on L1 naming with a mean score of 85% (SD=0.08) compared to 72% (SD=0.12). Cantonese-English speakers were younger, 10.69 (SD=9.6), and

Mandarin-Cantonese speaker were older, 21.08 (SD=13.29), when the L2 was learned. An ANOVA tested whether Group, L1 naming, L2 naming and AoA were associated with dependent variables, GMV observed in the LC and RC. No statistically relevant main effects or interactions were associated with the variance in GMV of each caudate.

5) Discussion

The current study aimed to further investigate the influence of lifelong bilingualism on neuroplasticity and cognitive performance. It was hypothesized that lifelong bilingualism would influence grey matter volume within the bilateral caudate. Bilinguals were predicted to exhibit leftward asymmetry in the bilateral caudate corresponding with the dominant role the left hemisphere has in executing language processes. Secondly, it was predicted that senior bilinguals would outperform monolinguals peers during the flanker task. It was hypothesized that that leftward asymmetry in the bilateral caudate would correlate with task performance amongst bilinguals.

The VBM analysis revealed that older bilingual participants exhibited significantly greater volume in the left caudate than in the right caudate, resulting in a leftward asymmetry in bilinguals (5.93%). Senior monolinguals exhibited a marginal rightward asymmetry (0.467%). The behavioral analysis revealed accuracy amongst both groups was high and performance was comparable, with bilinguals being slightly more accurate. Senior bilinguals demonstrated significantly faster reaction times across all conditions and during both runs of the experiment. The conflict effect was marginally significant during the second run, bilinguals exhibiting a smaller effect than monolinguals. However, the difference in conflict effects during the second run between groups was not significant. The structural-behavioral conjunction analysis revealed grey matter volume within the left caudate correlated with cognitive performance amongst bilinguals. Grey matter volume in the left caudate was positively correlated with percent accurate, and inversely correlated with reaction times. Greater grey matter volume in the left caudate in bilinguals was predictive of better accuracy and faster reaction times during the flanker task.

The variable, age, was initially positively correlated with the variance in grey matter volume of each caudate. In other words older age trended with more volume in each caudate. A regression analysis was run and the effect of age disappeared for the right caudate but remained for the left caudate, with an effect size of 7.5%. The effect of age disappeared for each group after running a post hoc analysis. It is possible that the association between the left caudate and age may have been influenced by total intracranial volume. Monolingual Italian speakers exhibited overall greater total intracranial volume, and accordingly a larger bilateral caudate, this may have skewed the data into revealing a relationship between age and grey matter volume in the bilateral caudate.

The influence of SES was assessed amongst 13 Cantonese-English bilinguals, 13 Mandarin-Cantonese bilinguals, and 15 Italian speakers were assessed. The results yielded no significant differences between the three groups. An ANOVA analysis revealed that grey matter volume in the left caudate was inversely correlated with social position, education, and the SES composite score. A post hoc analysis revealed that the SES composite score for Cantonese-English bilinguals was inversely correlated with the left caudate, where lower status predicted greater volume in the left caudate. No associations were revealed for the other groups. Lack of findings may be due to small sample sizes of each group. A larger sample size would have helped raise the statistical power of overall SES findings, helping to further determine whether socioeconomic variables influence to grey matter volume.

Bilinguals were given an L1 and L2 naming task, and a translation task. Bilinguals exhibited a low score in the L1 naming task 79% compared to monolinguals' 99.1%, and scored 63.9% in L2 naming, and 53.6% in the translation task. The origin as to why bilinguals scored so low on L1 naming is confounding, and consequently makes it difficult to interpret the level of L2 proficiency amongst bilinguals. There may have been weaknesses in the picture naming task design. Pictures may have been too complex for senior bilinguals, or participants may have had deficits in skills necessary to recognize orthography when translating. To avoid such perplexities, a practice run should be administered, and senior adults should be tested on writing, reading, and speaking in the L1 and L2. This would help account for deviations in performance, which may have been overlooked despite years of formal education.

5.1) Leftward and Rightward Asymmetry

This study aimed to assess neuroplasticity in a specific region regarding the bilingual language control network, the caudate nucleus. The left caudate has been associated with bilinguals' language switching behavior (Abutalebi & Green, 2008; Marien et al., 2005; Crinion et al., 2006; Abutalebi et al., 2008; Abutalebi et al., 2013), and together with the right caudate, this bilateral structure is also associated with task planning and the selection of target responses in other domains of cognitive processing (Luk et al., 2010; Abutalebi et al., 2011; Gold et al., 2013). Language processing is generally executed in the left hemisphere; it was therefore predicted that if bilinguals exhibited neuroplastic differences, it would concern the grey matter volume of the left caudate. Zou and colleagues (2012) also revealed greater grey matter volume within the left caudate of bimodal bilinguals compared to monolinguals. The leftward asymmetry (5.93%) that was found amongst older bilinguals in the current study suggests that neuroplastic changes result in greater grey matter volume in regions that respond to the demands of processing two languages, adapting the neurocognitive executive control network to meet greater processing demands.

Leftward asymmetry within the caudate nucleus has only been reported by a few studies: Gunning-Dixon et al., 1998; Szabo et al., 2003; Jiji et al. 2013. Jiji, Smitha, Gupta, Pillai, and Jayasree (2013) ran a quantitative volumetric analysis of the caudate nucleus in 15 AD patients (age range=57-73), 15 non-AD patients (age range=49-72), and 15 normal healthy volunteers (age range=29-65) from the Sree Chitra Tirunal Institute in Trivandrum, India. MRI findings revealed that the average volume of the left caudate was bigger than the right in healthy subjects, 0.486%; non-AD patients, 7.97%; and AD-patients, 14.05%, exhibiting greater atrophy in the right caudate. Jiji et al.'s (2013) study raises questions concerning the linguistic background of subjects. Considering the majority of Indian inhabitants speak a minimum of two languages, Indian L1 (Hindi, Urdi, etc.) and English L2 (learned in school), than the presumption for leftward asymmetry found amongst Jiji et al.'s (2013) subjects may be associated with bilingualism, and may perhaps protect the left caudate from accelerated atrophy.

The senior monolinguals from the current study exhibited a marginal rightward asymmetry, indicated by slightly larger right caudate. Patterns of rightward asymmetry are more commonly reported than leftward asymmetry (Peterson et al., 1993; Giedd et al., 1996; Ifthikharuddin et al., 2000; Larisch et al., 1998; Yamashita et al., 2009; Madsen et al., 2010). Madsen et al., (2010) analyzed 400 baseline structural MRI scans and reported rightward asymmetry amongst 300 individuals: 100 healthy elderly subjects (3.86%) and 200 elderly patients with mild cognitive impairments (2.13%). Rightward asymmetry was no longer detected amongst the 100 elderly patients with Alzheimer's disease. The analysis indicated that caudate atrophy correlated with general cognitive decline and impacted short-term and working memory for mildly impaired and AD patients, and atrophy was more accelerated in the right caudate. The current study showed senior bilinguals outperforming monolingual peers in a cognitive task; hence, no sign of cognitive impairment was observed. Therefore, the smaller right caudate cannot be a result of pathological atrophy in senior bilingual adults. However, the leftward asymmetry observed amongst senior bilinguals may reflect a reserve of grey matter volume as a result of continuously exercising the left caudate for dual-language processing.

A follow-up study with senior Cantonese or Mandarin control subjects could further investigate whether leftward asymmetry amongst bilinguals reflects a type of cognitive reserve.

In doing so, bilinguals may show greater bilateral volume, which could indicate more adept neurocognitive systems, similar to Luk et al.'s (2011) findings regarding greater white matter integrity in bilinguals. However, if monolinguals were to exhibit a rightward asymmetry, leftward asymmetry in bilinguals may be further indicative of bilingualism and neural compensation as proposed by Stern (2009), and suggested by Gold et al. (2013).

5.2) Cognitive Performance and Neuroplasticity

The second aim tested whether lifelong bilinguals would outperform monolinguals during a cognitive task, and whether leftward asymmetry would correlate with cognitive. Participants were assessed on accuracy and reaction time during a flanker task, a general cognitive task that requires response selection and inhibition during the facilitation and suppression of interference. Accuracy in both groups was high, with bilinguals slightly outperforming monolinguals. Bilinguals exhibited faster reaction times across all conditions than monolingual. Better accuracy and faster reaction times correlated with grey matter volume in the left caudate in bilinguals. Better accuracy was predictive of greater grey matter volume in the left caudate, and greater in the left caudate was predictive of faster reaction times.

Few neuroimaging studies have investigated neuroplasticity in the executive network relative to behavioral performance amongst bilingual participants (Abutalebi et al., 2011; Zou et al., 2012). Gold, Kim, Johnson, Kryscio, and Smith (2013) conducted such an investigation in older bilingual adults. Gold et al. (2013) examined the neural correlates associated with cognitive performance observed in younger and older bilinguals and their counterparts (4 groups of 20 participants). Cognitive performance was assessed using a perceptual color-shape task-switching paradigm. The fMRI analysis revealed older bilinguals exhibited better cognitive performance indicated by smaller switch costs as opposed to monolingual peers, while both younger groups performed equally well and outperformed older adults. Although older bilinguals outperformed monolingual peers, no differences in grey matter volume in conflict effect regions[6] were detected between the two older groups in the VBM analysis. Remarkably, differences in grey matter volume between younger and older groups were also unreported. No analysis was run on volume in conflict effects regions relative to cognitive performance.

According to the literature (Luk et al., 2011; Schweizer et al., 2012; Gold, Johnson & Powell 2013), older individuals normally exhibit some degree of general atrophy associated with ageing. The older bilinguals in Gold et al.'s (2013) study outperformed monolingual peers, while exhibiting poorer cognitive performance than younger adults. This suggests some degree of cognitive decline, presumably due to ageing (participants were healthy and non-pathological). Nonetheless, the VBM analysis did not report any regional differences in grey matter volumes between older and younger adults. It is possible that the VBM analysis may have been ineffective at detecting differences in grey matter volume; however, no analysis was included regarding grey matter volume in association with cognitive performance. The current study did report neuroanatomical differences in grey matter volume in older bilinguals, the left caudate was larger than the right, and this leftward asymmetry correlated with better cognitive performance. Both Zou et al. (2012) and Abutalebi et al. (2011) similarly reported that grey matter volume in the bilingual language control network correlated with better cognitive performance (smaller switch costs & conflict effects).

Zou et al. (2012) reported that bimodal bilinguals exhibited greater grey matter volume in the left caudate than monolingual subjects. The analysis did not further report on the asymmetry of the bilateral caudate in bilinguals, nor in monolinguals. By not including the index of asymmetry, the percent difference in volume between the left and right caudate, it is difficult to interpret whether the left caudate was also in fact larger than the right caudate. This exclusion weakens the argument that the leftward asymmetry is influenced by the greater

[6] The VBM analysis was run on the following regions that exhibited the most (BOLD signal) activation during the switch condition: bilateral dorsolateral prefrontal cortex, the bilateral the ventrolateral prefrontal cortex, the anterior cingulate cortex, and the bilateral supramarginal gyrus (Gold et al., 2013).

executive demand of bilingual language processing, influencing grey matter volume in the left caudate. The senior bilinguals in the current study did not exhibit a larger left caudate than monolinguals; however, a leftward asymmetry was detected in senior bilinguals. Hence, the current study argues that leftward asymmetry observed amongst older bilinguals is influenced by a lifetime of greater processing demands associated with two languages.

6) Future Research

The current study assessed neuroplastic differences in the bilateral caudate in bilinguals in association with general cognitive performance. A structural-behavioral analysis provides an account, albeit limited, of the structural basis of the network executing task goals. However, future research investigating the influence of lifelong bilingualism on neuroplasticity in the bilingual neurocognitive network should measure functional activation amongst neural correlates. By not including a functional analysis in the experimental design, it is impossible to assess how differences in neuroplasticity may influence the level of functional engagement during cognitive performance. This is especially important when distinguishing between older and younger, monolingual and bilingual adults on behavioral and neurocognitive performance and efficiency. Therefore, a functional analysis (i.e. fMRI, PET, EEG, SPECT) should be combined with a structural analysis (i.e. MRI, VBM, DTI, CT) when assessing for behavioral differences amongst bilingual and monolinguals subjects to attain the greatest amount of statistical power.

Furthermore, the task paradigm should be carefully considered when assessing behavioral performance in association with a particular neuroanatomical region or network concerning bilinguals. The current study tested cognitive performance on a flanker task. The flanker task is associated with the conflict effect and traditionally engages areas such as the anterior cingulate cortex, as well as the pre-supplementary motor areas (Luk et al., 2010; Abutalebi et al., 2012). The caudate nucleus is typically associated with the switching effect (Abutalebi et al., 2008; Ali et al., 2009; Zou et al., 2012; Gold et al., 2013). Therefore, a task switching paradigm may have been better suited for the study. Future studies should assess the structural and functional differences in the caudate nucleus amongst older bilinguals and older monolinguals by conducting verbal switching tasks (i.e. language and lexical, Abutelabi et al., 2008), and a perceptual switching task (i.e. color-shape task switching paradigm). By utilizing verbal and nonverbal switching tasks, which elicit a switching effect, the caudate nucleus is engaged in both language groups for both language processing and other cognitive domains.

In doing so, the magnitude of the switching effect can be assessed relative to the functional activation of the caudate nucleus; meanwhile, assessing whether differences in plasticity and asymmetry are associated with relevant functional and behavioral findings. The results of carrying out a behavioral structural-functional analysis would reveal whether older bilinguals exhibit greater cognitive performance (smaller switching effects) relative to the level of functional engagement and grey matter volume of the bilateral caudate. These findings would further benefit the ongoing discussion concerning the influence of lifelong bilingualism and cognitive reserve.

7) Conclusion

This thesis provided an account of the cognitive advantages associated with bilingualism from a psycholinguistic and neurological perspective. First, the thesis explored a few of the behavioral findings concerning greater executive performance of bilinguals when managing conflict and interference as opposed to monolinguals. Secondly, executive performance was mapped to the neuroanatomical underpinnings associated with carrying out those executive functions in linguistic and other cognitive domains. The aim was to bridge behavioral findings with functional and structural neuroimaging research that similarly assessed the bilingual neurocognitive network relative to the bilingual advantage. The literature provides an account of how bilingualism does not only affect cognitive performance, but impacts the brain on a functional and structural level. Furthermore, the question that arose is how bilingualism may influence ageing effects, and whether lifelong bilingualism provides cognitive benefits and a reserve against cognitive decline?

The current study investigated the cognitive advantages of bilinguals by investigating whether cognitive performance and neuroplasticity differed in senior bilingual adults. The results from this study indicate that bilingualism does influence cognitive performance and impacts neuroplasticity in older bilinguals. Older bilinguals outperformed their monolingual peers. Furthermore a difference in asymmetry was observed in the bilateral caudate, where older bilinguals were reported to exhibit leftward asymmetry, a larger left caudate nucleus than right. The leftward asymmetry revealed in this study correlated with better bilingual cognitive performance. It is therefore argued that leftward asymmetry in the bilateral caudate is influenced by the greater executive demands of processing two languages over a lifetime. Further research is necessary to investigate whether these findings can be replicated and to continue the discussion concerning the neurocognitive benefits of lifelong bilingualism.

References

Abutalebi, J., Annoni, J. M., Seghier, M., Zimine, I., Lee-Jahnke, H., Lazeyras, F., Lazeyras, F., Cappa, S. F., & Khateb, A. (2008). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex*, 18, 1496_1505.

Abutalebi, J., Rosa, P. A. D., Castro Gonzaga, A. K., Keim, R., Costa, A., & Perani, D. (2013a). The role of the left putamen in multilingual language production. *Brain and language*, *125*(3), 307-315.

Abutalebi, J., Della Rosa, P. A., Ding, G., Weekes, B., Costa, A., & Green, D. W. (2013). Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex*, *49*(3), 905-911.

Abutalebi, J., Della Rosa, P. A., Green, D. W., Hernandez, M., Scifo, P., Keim, R., Cappa, S. F., & Costa, A. (2011). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. *Cerebral cortex*, bhr287.

Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, 20, 242_275.

Abutalebi, J., & Green, D. W. (2008). Control mechanisms in bilingual language production: Neural evidence from language switching studies. *Language and Cognitive Processes*, 23, 557_582.

Abutalebi, J., Miozzo, A., & Cappa, S. F. (2000). Do subcortical structures control language selection in bilinguals? Evidence from pathological language mixing. *Neurocase*, 6, 101_106.

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychology and aging*, *19*(2), 290.

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(4), 859.

Bialystok, E., Craik, F. I., & Luk, G. (2012). Bilingualism: Consequences for mind and brain. *Trends in cognitive sciences*, *16*(4), 240-250.

Bialystok, E., Craik, F. I., & Ryan, J. (2006). Executive control in a modified antisaccade task: Effects of aging and bilingualism. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(6), 1341.

Bialystok, E., & Martin, M. M. (2004). Attention and inhibition in bilingual children: Evidence from the dimensional change card sort task. *Developmental science*, *7*(3), 325-339.

Bialystok, E., & Viswanathan, M. (2009). Components of executive control with advantages for bilingual children in two cultures. *Cognition*, *112*(3), 494-500.

Brysbaert, M. (1998). Word recognition in bilinguals: Evidence against the existence of two separate lexicons. *Psychologica Belgica*, 38, 163–175.

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition*, 106, 59–86.

Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., ... & Price, C. J. (2006). Language control in the bilingual brain. *Science*,*312*(5779), 1537-1540.

Crum, R. M., Anthony, J. C., Bassett, S. S., & Folstein, M. F. (1993). Population-based norms for the Mini-Mental State Examination by age and educational level. *Jama*, *269*(18), 2386-2391.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual review of neuroscience*, *18*(1), 193-222.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: changes in grey matter induced by training. *Nature*, *427*(6972), 311-312.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & psychophysics*, *16*(1), 143-149.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of cognitive neuroscience*, *14*(3), 340-347.

Folstein MF, Folstein SE, McHugh PR (1975). ""Mini-mental state". A practical method for grading the cognitive state of patients for the clinician". *Journal of Psychiatric Research* **12** (3): 189–98.

Frisoni, G., Rossi, R., and Beltramello, A. (2002). The radial width of the temporal horn in mild cognitive impairment. *Journal of Neuroimaging,* 12(4): 351-354.

Francis, W. (1999). Cognitive integration of language and memory in bilinguals: Semantic representation. *Psychological Bulletin*, 125, 193–222.

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., Paus, T., Evans, A. C., & Rapoport, J. L. (1999). Brain development during childhood and adolescence: a longitudinal MRI study. *Nature neuroscience*, *2*(10), 861-863.

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *The Journal of Neuroscience*, 33(2), 387-396.

Gold, B. T., Johnson, N. F., & Powell, D. K. (2013). Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. *Neuropsychologia*, 51(13), 2841-2846.

Gollan, T. H., & Kroll, J. F. (2001). The cognitive neuropsychology of bilingualism. In B. Rapp (Ed.), What deficits reveal about the human mind/brain: A handbook of cognitive neuropsychology (pp. 321–345). Philadelphia: Psychology Press.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and cognition*, *1*(02), 67-81.

Green, D. W., & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, *25*(5), 515-530.

Gunning-Dixon, F. M., Head, D., McQuain, J., Acker, J. D., & Raz, N. (1998). Differential aging of the human striatum: a prospective MR imaging study. *American Journal of Neuroradiology*, *19*(8), 1501-1507.

Ifthikharuddin, S. F., Shrier, D. A., Numaguchi, Y., Tang, X., Ning, R., Shibata, D. K., & Kurlan, R. (2000). MR volumetric analysis of the human basal ganglia: normative data. *Academic radiology*, *7*(8), 627-634.

Jiji, S., Smitha, K. A., Gupta, A. K., Pillai, V. P. M., & Jayasree, R. S. (2013). Segmentation and volumetric analysis of the caudate nucleus in Alzheimer's disease. *European journal of radiology*, *82*(9), 1525-1530.

Kroll, J. F., & Dijkstra, A. (2002). The bilingual lexicon. In R. Kaplan (Ed.), Handbook of applied linguistics (pp. 301–321). Oxford, England: Oxford University Press.

Larisch, R., Meyer, W., Klimke, A., Kehren, F., Vosberg, H., & Muller-Gartner, H. W. (1998). Left-right asymmetry of striatal dopamine D2 receptors. *Nuclear medicine communications*, *19*(8), 781-788.

Leh, S. E., Ptito, A., Chakravarty, M. M., & Strafella, A. P. (2007). Fronto-striatal connections in the human brain: a probabilistic diffusion tractography study. *Neuroscience letters*, *419*(2), 113-118.

Liu, H., Hu, Z., Guo, T., & Peng, D. (2010). Speaking words in two languages with one brain: Neural overlap and dissociation. *Brain Research*, 1316, 75_82.

Luk, G., Anderson, J. A., Craik, F. I., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition versus interference suppression. *Brain and cognition*, *74*(3), 347-357.

Luk, G., Bialystok, E., Craik, F. I., & Grady, C. L. (2011). Lifelong bilingualism maintains white matter integrity in older adults. *The Journal of Neuroscience*,*31*(46), 16808-16813.

Luk, G., Green, D. W., Abutalebi, J., & Grady, C. (2012). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Language and cognitive processes*, *27*(10), 1479-1488.

Madden, D. J., Spaniol, J., Costello, M. C., Bucur, B., White, L. E., Cabeza, R., Davis, S. W., Dennis, N. A., Provenzale, J. M., Huettel, S. A. (2009). Cerebral white matter integrity mediates adult age differences in cognitive performance. *Journal of Cognitive Neuroscience* 21:289 –302.

Madsen, S. K., Ho, A. J., Hua, X., Saharan, P. S., Toga, A. W., Jack Jr, C. R., Weiner, M. W., & Thompson, P. M. (2010). 3D maps localize caudate nucleus atrophy in 400 Alzheimer's disease, mild cognitive impairment, and healthy elderly subjects. *Neurobiology of aging*, *31*(8), 1312-1325.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, *97*(8), 4398-4403.

Maldjan, J.A., Laurienti, P.J., Kraft, R.A., Burdette, J.H., 2003. An automated method for neuroanatomic and cytoarchitetonic atlas-based interrogation of fMRI sata sets. *NeuroImage* 19, 1233-1239.

Maldjan, J.A., Laurienti, P.J., Burdette, J.H., 2004. Precentral gyrus discrepancy in electronic versions of the Talairach atlas. *NeuroImage* 21, 450-455.

Manjon, J.V., Coupe, P., Marti-Bonmati, L., Collins, D.L., Robles M., 2010. Adaptive non local means denoising of MR images with spatially varying noise levels. J Magn Reson Imaging 31, 192-203.

Marien, P., Abutalebi, J., Engelborghs, S., & De Deyn, P. P. (2005). Acquired subcortical bilingual aphasia in an early bilingual child: Pathophysiology of pathological language switching and language mixing. Neurocase, 11, 385_398.

Mazziotta, J., Toga, A., Evans, A., Fox, P., Lancaster, J., Zilles, K., et al., 2001. A probabilistic atlas and reference system for the human brain (ICBM). *Phil Trans Royal Society B* 356, 1293-1322.

Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., & Price, C. J. (2004). Neurolinguistics: structural plasticity in the bilingual brain. *Nature*, *431*(7010), 757-757.

Mechelli, A., Price, C. J., Friston, K. J., & Ashburner, J. (2005). Voxel-based morphometry of the human brain: methods and applications. *Current Medical Imaging Reviews*, *1*(2), 105-113.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience*, *24*(1), 167-202.

Mungas, D. (1991). Iii-office mental status testing: A practical guide. *Geriatrics*,*46*(7).

Peal, E., & Lambert, W. E. (1962). The relation of bilingualism to intelligence. *Psychological Monographs: general and applied*, *76*(27), 1-23.

Peterson, B., Riddle, M. A., Cohen, D. J., Katz, L. D., Smith, J. C., Hardin, M. T., & Leckman, J. F. (1993). Reduced basal ganglia volumes in Tourette's syndrome using three-dimensional reconstruction techniques from magnetic resonance images. *Neurology*, *43*(5), 941-941.

Perani, D., Paulesu, E., Galles, N. S., Dupoux, E., Dehaene, S., Bettinardi, V., Cappa, S. F., Fazio, F., & Mehler, J. (1998). The bilingual brain. Proficiency and age of acquisition of the second language. *Brain*, *121*(10), 1841-1852.

Robinson, J.L. et al. (2012). The functional connectivity of the human caudate: An application of meta-analytic connectivity modeling with behavioral filtering. *NeuroImage*, 60, 117-129.

Rodriguez-Fornells, A., Van Der Lugt, A., Rotte, M., Britti, B., Heinze, H. J., & Münte, T. F. (2005). Second language interferes with word production in fluent bilinguals: brain potential and functional imaging evidence. *Journal of Cognitive Neuroscience*, *17*(3), 422-433.

Roelofs, A. (1998). Lemma selection without inhibition of languages in bilingual speakers. *Bilingualism: Language and Cognition*, *1*(02), 94-95.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, *42*(8), 1029-1040.

Saer, D. J. The effects of bilingualism on intelligence. Brit. J. Psychology, 1923, 14, 25-38.

Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I., & Bialystok, E. (2012). Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer’s disease. *Cortex*, 48(8), 991-996.

Smith, F. Bilingualism and mental development. Brit. J. *Psychology*, 1923, 13, 270-282.

Smith, M. C. (1997). How do bilinguals access lexical information? In A. M. B. de Groot & J. F. Kroll (Eds.), Tutorials in bilingualism: Psycholinguistic perspectives (pp. 145–168). Mahwah, NJ: Erlbaum.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of experimental psychology: Human learning and memory*,*6*(2), 174.

Stern Y. Cognitive reserve. Neuropsychologia, 47(10): 2015-2028, 2009.

Szabó, C. Á., Lancaster, J. L., Xiong, J., Cook, C., & Fox, P. (2003). MR imaging volumetry of subcortical structures and cerebellar hemispheres in normal persons. *American Journal of Neuroradiology*, *24*(4), 644-647.

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., & Joliot, M. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *Neuroimage*, 15(1), 273-289.

Wang, Y., Xue, G., Chen, C., Xue, F., & Donga, Q. (2007). Neural bases of asymmetric language switching in second-language learners: An ER-fMRI study. *NeuroImage*, 35, 862_870.

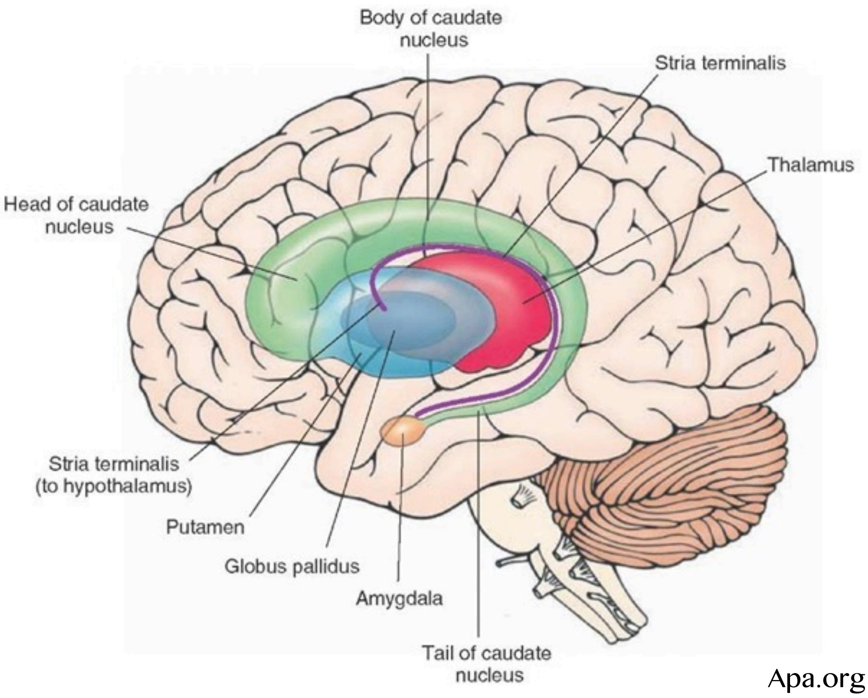
Yamashita, K., Yoshiura, T., Hiwatashi, A., Noguchi, T., Togao, O., Takayama, Y., Nagao, E., Kamano, H., Hatakenaka, M., & Honda, H. (2009). Volumetric asymmetry and differential aging effect of the human caudate nucleus in normal individuals: a prospective MR imaging study. *Journal of Neuroimaging*, *21*(1), 34-37.

Zhang, Y., Londos, E., Minthon, L., Wattmo, C., Liu, H.J., Aspelin, P., et al. (2008)Usefulness of computed tomography linear measurements in diagnosing Alzheimer's disease. *Acta Radiologica*, 49(1): 91-97.

Zou, L., Ding, G., Abutalebi, J., Shu, H., & Peng, D. (2012). Structural plasticity of the left caudate in bimodal bilinguals. *cortex*, *48*(9), 1197-1206.

Appendix

Figure 1.) Basal Ganglia - Caudate Nucleus



Apa.org

Picture Naming Task Stimuli

English stimuli:

Eagle; Giraffe; Goat; Monkey; Necklace; Nut; Roller skate; Spider; Wagon; Whistle; Airplane; Bird; Celery; Guitar; Piano; Pliers; Potato; Pumpkin; Suitcase/Box; Tennis racket; Arm/Hand; Book; Comb; Ear; Lips; Pants/Trousers; Shoe; Toe; Train; Watch.

Cantonese stimuli:

Barrel; Caterpillar; Clown; Crown; Elephant; French Horn; Kangaroo; Owl; Sea Horse; Strawberry; Butterfly; Duck; Hammer; Iron; Lamp; Motorcycle; Nail; Nail file; Pitcher; Screwdriver; Bed; Belt; Blouse; Finger; Jacket; Light Bulb; Pencil; Plug; Pocketbook; Toothbrush.

Mandarin Stimuli:

Bear; Beetle; Flute; Traffic Light; Grasshopper; Harp; Lion; Spinning Wheel; Top; Windmill; Cap; Horse; Mountain; Pear; Rabbit; Snake; Turtle; Watering Can; Window; Wrench; Boot; Clock; Corn; Desk; Dress; House; Nose; Scissors; Stool; Telephone.

Stimuli for naming tasks

Cantonese	Mandarin	English
袋鼠	連衣裙	Watch
海馬	馬	Train
水壺	獅子	Tennis racket
外套、褸	房子、屋	Lips
鉛筆	烏龜	Book
蝴蝶	蛇	Necklace
書包、袋	帽子	Roller skate
皇冠	山、雪山	Whistle
牙刷	電話	Bird
外衣、褸	桃子	Eagle
燈籠	澆水壺、水壺	Celery
電單車	窗户	Spider
手指、食指	螞蚱、草蜢	Comb
釘	鼻子	Guitar
螺絲批	扳手	Ear
床	皮靴、鞋子	Piano
台燈、燈	笛子	Potato
錘	座鐘	Shoe
熨斗	熊	Monkey
圓號、喇叭	紡車、衣車	Airplane
指甲鉗	寫字台	Wagon
小丑	紅綠燈	Pliers
皮帶	豎琴	Pumpkin
插頭	兔子	Suitcase
士多啤梨、草莓	磨坊、風車	Nut
大象	陀螺	Arm、hand
桶	剪子、剪刀	Pants、trousers
鴨	圓凳、凳	Toe
毛蟲、蟲	玉米	Giraffe
貓頭鷹	甲蟲	Goat

Translation task Frequency Lists: Cantonese L1 to English L2

Stimuli for translation task

High frequency		**Medium frequency**		**Low frequency**	
男人	man/men	膊頭/肩膀	shoulder	資產	asset
口	mouth	主人	master/Host/Owner/lord	青年	youth/ teenager
魚	fish	角落	corner	覆蓋	cover
探訪	visit	火柴	match	費用	fee/charge
麻煩 (n)*	trouble/ annoyance	婚姻	marriage	噪音	noise
付款 (n)*	payment	罪行	crime/Sins	槍	gun
女士	woman/ lady/ female	真相	truth	護士	nurse
假期	holiday/ vacation	安全 (n)*	safety	箭	arrow
重要 (n)*	importance	信任 (n)*	trust	部隊	troop/army
椅子	chair	痛苦 (n)*	pain	時尚 (n)*	fashion
內容	content	危機	danger/Crisis	屋頂	roof
卡	card	評估 (n)*	assessment /appraisal/ evaluation	撕裂	tear
溝通 (n)*	communication	耕種	farm	律師	lawyer
太陽	sun	僱主	employer	成就	achievement
女人	woman/ lady/ female	連接 (n)*	connection	囚犯	prisoner/inmate
主席	president/ chairman/ chairperson	債	debt/load	女性	female/woman/ lady
講座	talk/ seminar/ lecture	木	wood	乘客	passenger
河流	river	跑	run	根	root
屋	house	農夫	farmer	欄	column
反對 (n)*	opposition/ objection	交通	traffic	製造商	manufacturer/ producer
意見	opinion/ view	歌曲	song	形成 (n)*	formation
星星	star(s)	晚餐	dinner	廢料	waste

*Note: (n) means the target translations were told to be nouns.

Figure 1.a) Bar Graph, Average GMV in each Caudate per Language Group

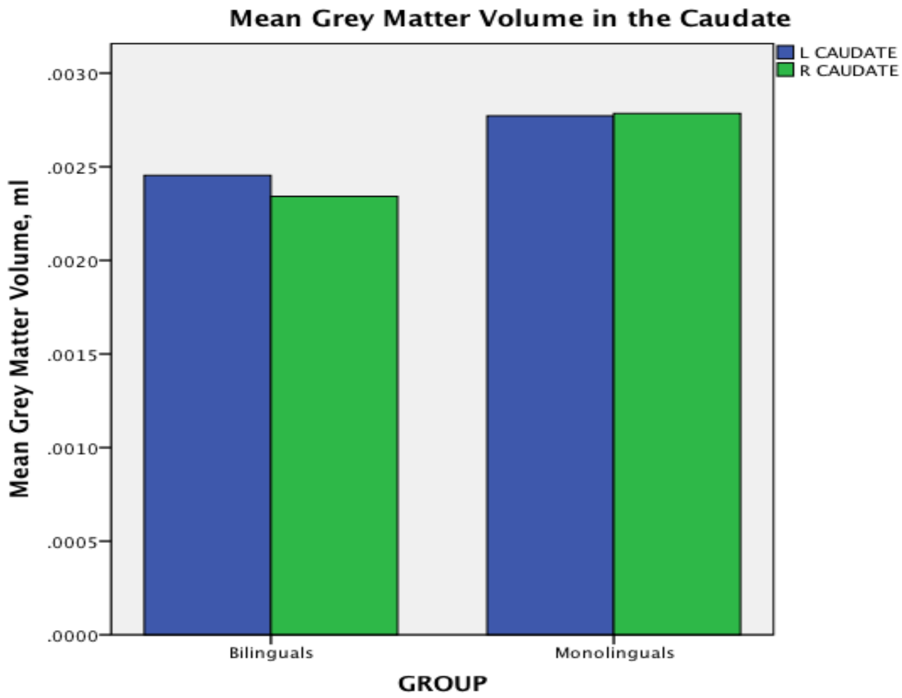


Figure 1.b) Regression Model

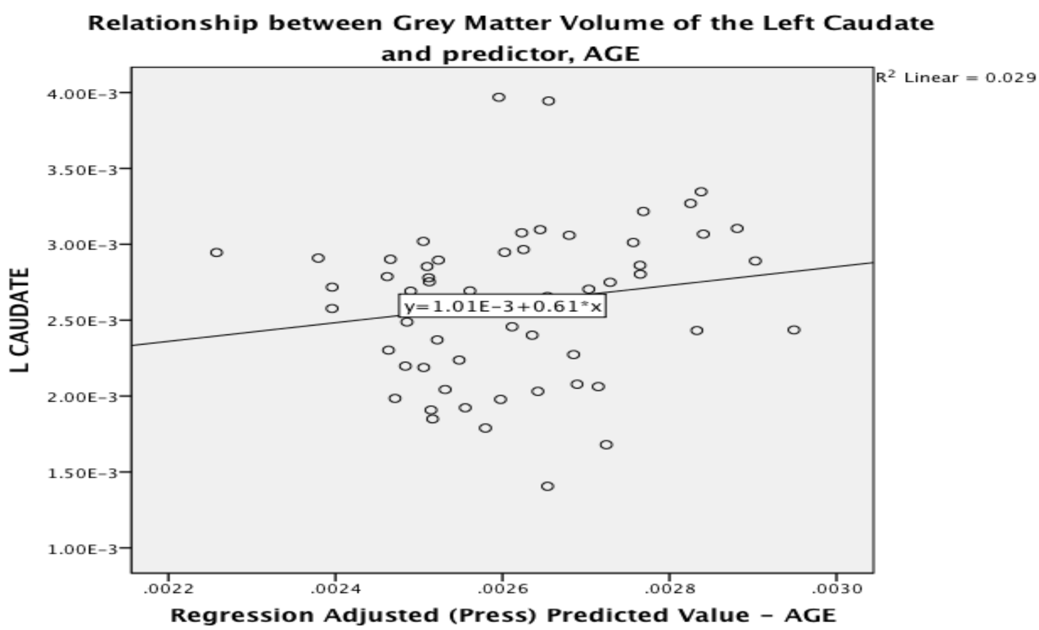


Figure 1.c) One-way ANOVA, Composite Z-Score Means

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Media_C_1	Between Groups	128806.241	1	128806.241	10.555	.002
	Within Groups	659000.004	54	12203.704		
	Total	787806.246	55			
Media_I_1	Between Groups	126656.441	1	126656.441	5.299	.025
	Within Groups	1290707.411	54	23901.989		
	Total	1417363.851	55			
Media_N_1	Between Groups	116816.913	1	116816.913	10.392	.002
	Within Groups	606993.146	54	11240.614		
	Total	723810.059	55			
Media_C_2	Between Groups	62571.747	1	62571.747	5.948	.018
	Within Groups	568029.261	54	10519.060		
	Total	630601.008	55			
Media_I_2	Between Groups	110634.370	1	110634.370	6.061	.017
	Within Groups	985686.409	54	18253.452		
	Total	1096320.778	55			
Media_N_2	Between Groups	72308.304	1	72308.304	6.582	.013
	Within Groups	593189.287	54	10984.987		
	Total	665497.591	55			

Figure 1.d) Average Percent Accurate on Proficiency Tasks

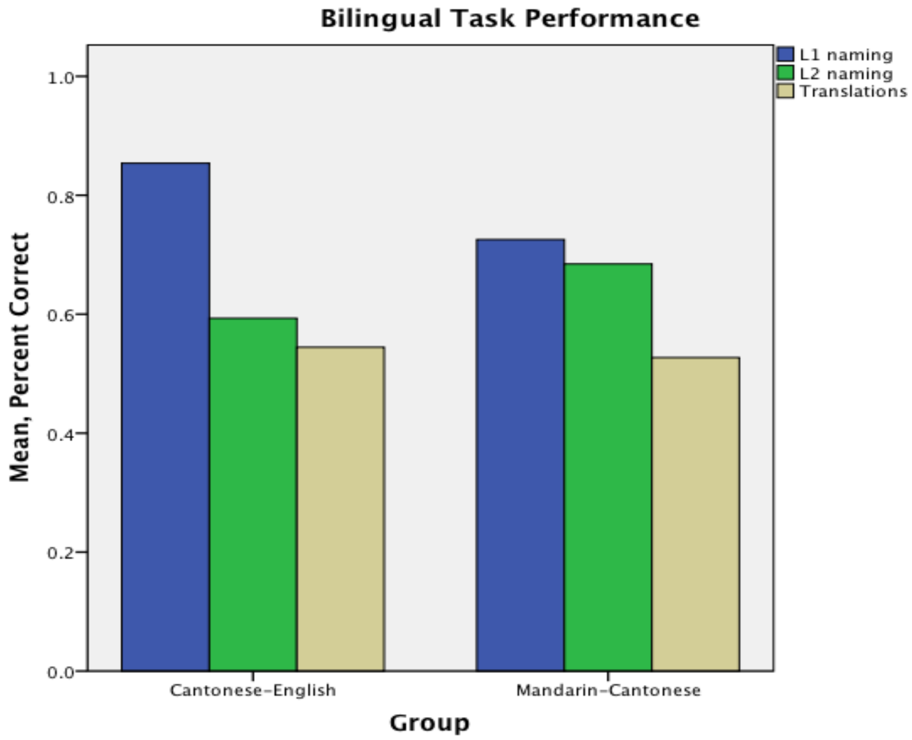


Figure 1.e) GMV in the Caudate Nucleus amongst Bilingual Groups