Functional and Structural Plasticity in the Bilingual Brain

Esli Struys
Functional and Structural Plasticity
in the Bilingual Brain
An Investigation into the Development of Cognitive Processing
in Bilingual Populations

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Ten slotte wil ik Els bedanken voor haar grondige review van deze hele dissertatie vanuit a comfortable chair in a dimly-lit room.

Esli Struys

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Introduction

One year ago, the *New York Times* published an article entitled “Why Bilinguals Are Smarter” (Bhattacharjee, 2012). Summarizing recent scientific evidence in support of this statement, it was argued that speaking multiple languages leads to advantages that go beyond the domain of language. Bilingualism, it was said, has an impact on general cognitive functioning in children and adults, and even delays the onset of dementia in the elderly. Just as they have to deal with different languages, bilinguals are assumed to be better at processing different sources of information. This higher flexibility makes a bilingual smarter.

The notion of enhanced cognitive abilities in bilinguals may sound familiar to the average newspaper reader; yet still up to the 1960s most scientists thought that bilingualism only had negative repercussions for the development of intelligence and cognitive functioning. In a landmark study that initiated a paradigm shift in the scientific thinking about bilingualism and cognition, Peal and Lambert (1962) reported better scores for bilinguals on verbal and nonverbal intelligence tests, a finding which was related to greater mental flexibility. These results were contrasted with an extensive list of literature that showed a detrimental impact of bilingualism on cognitive functioning (Darcy, 1953). Unlike previous studies, Peal and Lambert (1962) investigated cognitive functioning in bilinguals by carefully controlling for individual characteristics such as socioeconomic status and gender. Progressively, researchers started to realize that, when isolated from these potentially confounding variables, bilingualism might have an enhancing rather than a detrimental impact on cognition in spite of previous assumptions.

Despite this scientific paradigm shift, earlier misconceptions about bilingualism-induced poor cognitive functioning have survived into our era. Still 50 years after Peal and Lambert’s report (1962), many people, even those holding responsible positions in education or politics, attribute societal problems as migrants’ language deficiency, school drop-out or inferior intelligence to the frequent use of more than one language instead of to such confounding variables as an individual’s lower socioeconomic status. One sad example of this is the usage of the term ‘zerolingualism’ by
the previous Flemish Minister of Education to denote the risks of multilingual education for pupils with lower language or cognitive abilities (Vandenbroucke, 2007).

This dissertation: why?

This dissertation attempts to offer a contribution to debates on the effect of bilingualism on cognitive development. The main focus of this dissertation lies on different types of plasticity in the bilingual brain. In this context, plasticity refers to the flexibility of the human brain to adapt to different environments. The study of neural plasticity has emerged as a fruitful field for understanding the interaction between the structure of our brain and the environments to which we are exposed (Pascual-Leone, Amedi, Fregni, & Merabet, 2005). Bilingualism has turned out to be one of the main experiential factors that contribute to our knowledge of plasticity (Mechelli et al., 2004).

In this dissertation, functional plasticity in the multilingual brain will be examined by looking at controlled processing in the multilingual brain. Controlled processing, cognitive control or executive functioning are umbrella terms that are used to refer to a number of related processes that regulate, control and manage other cognitive activities (Alvarez & Emory, 2006; Chan, Shum, Toulopoulou, & Chen, 2008). The presence of two or more languages in the bilingual mind requires control over these different systems. A certain degree of overlap is expected between language control and more general types of controlled processing. The central research question of this dissertation goes as follows: “What are the effects of bilingualism on the development of cognitive control in the brain and on the brain structures that enable bilingual language processing?”

As can be deduced from a little quest on any web search engine, this theme has triggered many publications and heated discussions over the last decade and the question might arise what else, if anything, is yet to be said. Despite the high number of studies on the topic of this dissertation, no convergence has been reached on whether or not bilingualism leads to enhanced controlled processing. One very recent article was even provocatively entitled ‘There is no coherent evidence for a bilingual advantage in executive functioning’ (Paap & Greenberg, 2013). This dissertation will argue that it would be wrong to expect any bilingual
advantage due to the high degree of variability between bilingual individuals as to their language control abilities. In spite of the growing number of studies on controlled processing in bilinguals, this dissertation adds eight novelties to this research theme (see Table 0.1).

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Table 0.1 Eight novelties this dissertation adds to the research theme of controlled processing in bilinguals.

First, this dissertation is the product of a linguist with a wide interest in general linguistic theory and a firm background in various branches of language studies, including both its social and psychological aspects. So far, most studies on controlled processing in bilinguals have been carried out by experimental psychological research groups. This means that most attention has been devoted to methodological aspects of bilingual effects, such as the exact task features required to perceive group differences (e.g., Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009). Little attention, however, has been given to the vast amount of variability between bilingual individuals. From a linguist’s perspective, it might be stunning to read studies with bilingual groups that were composed of individuals with widely varying language backgrounds (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004). Another drawback of a purely psychological perspective is the lack of objective measurements to test language proficiency or the absence of key background information such as the manner of second language acquisition (e.g., Kousaie & Phillips, 2012). If quantitative measures were included, most often only one language (e.g., L2) or one aspect of language processing (e.g., semantics) was tested (e.g., Bialystok et al., 2004; Bialystok, Martin, & Viswanathan, 2005; Morton & Harper, 2007).

The added value of a linguist’s perspective is that more attention is given to the link between how a bilingual manages his or her two language systems
in real-life communicative settings and the attested advantages in laboratory settings. This can be accomplished by providing a total picture of all aspects of the development of a bilingual individual, including such factors as the age and manner of (second) language acquisition, proficiency in all the languages involved, and language control abilities. A link between bilingualism and cognition cannot be fully understood without acknowledging that any bilingual individual is raised in a particular language environment with social aspects that have an impact on the psycholinguistic development.

Second, as the title of this dissertation indicates, both functional and structural plasticity in the bilingual brain will be scrutinized. Functional or representational plasticity refers to the well documented phenomenon that the neuronal tissue that underlies particular skills may expand or contract, either in response to a lesion or by experience alone (Donoghue, 1995). Bilingualism is one of the experiential factors that have an effect on the neuronal representation of language and cognition (Perani & Abutalebi, 2005). Structural plasticity can be described as changes in the size and quality of neural structures, caused by the same two causes: impairment and environment. The brain is made up of billions of neurons. These nerve cells are composed of bodies with nuclei that form the grey matter of the brain, and of input and output structures in charge of communication with other neurons that form the white matter of the brain. Bilingualism-induced structural plasticity can be observed both in grey and white matter (Bialystok, Craik & Luk, 2012). One of the key questions in this dissertation is what factors related to bilingualism induce functional and structural plasticity in the human brain.

The rapid development of neuroimaging techniques over the last decades has made possible the study of neural representation of language in healthy populations. In all neuroimaging studies reported in this dissertation, magnetic resonance imaging (MRI) was used to visualize brain structure and neural activity. An MRI scanner (see Figure 0.1) generates a powerful magnetic field which aligns the magnetization of specific nuclei of atoms in the body. During an MRI examination, non-invasive radiofrequency pulses are applied by the machine to alter the alignment of this magnetization. The radio frequency signal that these atomic nuclei produce as a reaction to these pulses can be detected by the scanner and is converted to a 3D image.
Two specialized MRI scans were used in this dissertation to investigate functional and structural plasticity. Functional magnetic resonance imaging (fMRI) was used to measure neurofunctional correlates of controlled processing. fMRI is a hemodynamic (literally meaning ‘blood movement’) functional neuroimaging technique based on the blood-oxygen-level-dependent (BOLD) mechanism (Huettel, Song & McCarthy, 2009). Neural activity increases the need for oxygenated blood in specific regions, the impact of which can be detected by the MRI scanner. Diffusion tensor imaging (DTI) was applied to visualize structural plasticity in bilinguals. DTI measures the diffusion of water molecules in the brain; it is commonly used to track the connectivity of white matter in the brain (e.g., Scholz, Klein, Behrens, & Johansen-Berg, 2009).

Third, this dissertation builds further on a newly emerging distinction between automatic and controlled processing in the study of neural correlates of bilingual language processing (Abutalebi & Green, 2007). This distinction has the potential to replace the outdated, but still influential Wernicke-Geschwind model of neural language processing (Geschwind, 1970), according to which language processing can be decomposed into two basic functions: comprehension and speaking. Each of these functions are subserved by different language centers in the brain: Wernicke’s area is
supposed to underlie speech comprehension, whereas Broca’s area is responsible for language output. Recent neurolinguistic research has challenged this view by showing that Broca’s area is also implicated in speech processing (Caplan, 2006) and that speaking is even possible without Broca’s area (Plaza, Gatignol, Leroy, & Duffau, 2009). Moreover, neuroimaging has shown that on a wide variety of language tasks, the recruitment of Broca’s and Wernicke’s area is supplemented by neural activity in a network of domain-general controlled processing (Abutalebi & Green, 2007). An alternative view to the Wernicke-Geschwind model posits that Wernicke’s, Broca’s and other language-related areas subserve automatic (input and output) language processing, whereas language-nonspecific neural regions are in charge of controlled language processing.

The topic of automatic and controlled language processing is highly relevant to the topic of this dissertation. A better understanding of the degree of controlled processing that is required in different aspects of bilingual language use can elucidate the causes of enhanced cognitive processing in certain bilingual populations. In fact, most of the cognitive tasks on which bilinguals show an advantage recruit the same neural regions that are involved in controlled language processing, such as when two languages have to be processed at the same time or when using a less proficient language (Abutalebi, 2008). Crucially, the distinction between automatic and controlled processing in the language domain shows that many of the processes underlying bilingual language abilities are shared to a certain extent with other cognitive activities. An in-depth study of controlled processing in bilinguals may thus lead to an improved understanding on why bilingual advantages go beyond the domain of language.

Fourth, in all studies on controlled processing reported in this dissertation, analyses of behavioural performance in terms of speed and accuracy will be complemented by analyses of functional neuroimaging data. The aim is not to reveal what neural regions are active in a specific group of bilinguals during cognitive processing, but rather to explain the neurofunctional correlates of behavioural differences. This can be done at a group level by conducting statistical comparisons between various bilingual populations, or at an individual level by correlating patterns of neural activity to the speed of cognitive processing. In line with the previously described
distinction between automatic and controlled processing, the degree to which the neural control network is activated in different tasks and populations will receive ample attention.

Fifth, this dissertation investigates plasticity and controlled processing in different bilingual populations. Many studies that purely try to trace bilingual advantages by comparing one group of bilinguals to a matched group of monolinguals have been unsuccessful in revealing the nature and underlying causes of these advantages (e.g., Paap & Greenberg, 2013). In contrast, this dissertation will examine bilingual populations from different age groups, with different onset ages of second language acquisition or proficiency levels and with divergent language control abilities. Doing so turned out to be crucial for isolating the factors that are responsible for functional and structural plasticity in the bilingual brain.

Sixth, this dissertation will deal with developmental aspects of controlled processing in bilinguals by reporting data from the first longitudinal study that has ever been conducted on this topic in children. This long-term approach can elucidate some of the outstanding questions, such as why bilingual advantages are often only seen in early childhood and at older age, but not when individuals are at the peak of their attentional abilities (Bialystok et al., 2004). Possibly, bilingual advantages do not manifest themselves at separate points of time, but only by differences in the development of controlled processing skills. In addition to these repeated observations in the same groups of children, cross-sectional designs have been used to study bilingual effects in different groups of young adults, including simultaneous and sequential bilinguals and interpreters.

Seventh, all studies in this dissertation were conducted in Brussels. Being the multilingual capital city of the most globalized country in the world (Dreher, 2006), Brussels is undoubtedly one of the best places to carry out research on the effects of bilingualism on cognition in different populations. The 2013 Language Barometer, a large-scale language survey, revealed that 104 home languages are spoken in Brussels, which is a 50% increase over the past 12 years (Janssens, 2013). Furthermore, multilingualism is increasingly becoming the norm in the capital of Belgium. Even though Brussels only has two official languages (Dutch and French), these languages are only rarely the sole home language. For the first time in recent history, young Brusselers are more likely to be exposed to two
languages at home than to be raised monolingual. Interestingly, the percentage of simultaneous Dutch-French bilinguals is on the rise, with an increase from 9% in 2000 to 14% this year. Another interesting phenomenon in Brussels is the status of Dutch-language education, which has become a pole of attraction for non-native speakers of Dutch. Whereas most pupils in Dutch-speaking education used to be raised in monolingual families, they now often come from mixed-language families. This creates a large group of sequential bilinguals who speak one language at home and another at school. Brussels, thus, offers the perfect language sociological environment to test cognitive processing in different bilingual populations.

Finally, this dissertation will present a combined psycho- and sociolinguistic theory of bilingual’s executive functioning and its neurofunctional and structural correlates. This theory intends to fill an important gap in the literature on controlled processing in bilinguals. While some studies have argued against the existence of bilingual advantages in cognitive control (Morton & Harper, 2007; Paap & Greenberg, 2013), the large amount of studies that found enhanced cognitive processing in bilinguals (e.g., Costa, Hernández, & Sebastián-Gallés, 2008; Hilchey & Klein, 2011) cannot easily be ignored. The theory that will be elaborated in the last part of this dissertation posits that these contradictory results can be explained by individual differences in language control abilities. According to this theory, these psycholinguistic differences, in turn, can be related to sociolinguistic factors.

This dissertation: contents

This dissertation is built around three studies that were conducted from 2010 to 2013 in the framework of an interdisciplinary HOA project (Horizontale Onderzoeks Actie / Horizontal Research Action) financed by the Research Council (Onderzoeksraad, OZR) of the Vrije Universiteit Brussel (VUB) (see Table 0.2). These studies were conducted by an interdisciplinary team composed of linguists from the Multilingual Research Unit (MuRe) of the VUB Centre of Linguistics (CLIN) and of physicists and biomedical engineers from the VUB Department of Neuroimaging (BEFY). This project succeeds a previous long-term project on linguistic, arithmetic, and cognitive processing in bilingual children (Mondt, 2007; Mondt et al., 2011).
The main body of this dissertation reports data from a longitudinal study with 54 children who were around nine years of age at the first time of measurement (2010, T1) and two years older at the second measurement (2012, T2). Initially, the aim of this research was to reveal behavioural and neural correlates of cognitive control in two bilingual populations. Bilingual participants were labeled as ‘simultaneous bilingual’ if they were raised bilingual at home, and as ‘sequential bilinguals’ if they spoke French at home and learned Dutch at school. All participants underwent an extensive language test battery at T1. Two robust measures of cognitive control were included: a Simon task (Simon & Rudell, 1967) and a numeric Stroop task (Kaufmann et al., 2008). Correlation analyses were conducted to examine the degree of overlap between language and cognitive control.

In between the two time points, it became evident that language control is the most reliable predictor of cognitive control skills. Therefore, only a language control task was included at T2. Exactly the same tasks were repeated inside the MRI scanner. An Attention Network Test (ANT) was administered outside the MRI scanner. On both time points, structural plasticity was investigated by using DTI.

The longitudinal study with children was complemented by two cross-sectional studies in young adults. The wider aim of these experiments was to study individual variability in language and cognitive control in a sample of highly proficient bilingual individuals. In cross-sectional study I, a group of interpreters was compared to simultaneous bilinguals. Both groups had equal levels of language proficiency but their onset ages of acquisition and lengths of accumulated exposure were different. This research design allowed an investigation of the effects of lifelong bilingualism on neural structure.

In cross-sectional study II, the degree of overlap in behavioural and neural correlates between language and cognitive control was examined in two bilingual populations of young adults. Participants were grouped according to their onset ages of acquisition and their language control abilities into two groups. Inside the MRI scanner, all subjects performed a cognitive control (Simon task) and a language control task (two-language semantic categorization). Outside of the scanner, the participants were administered a short language test battery.
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<td>2010</td>
<td>54 children (mean age = 9 years)</td>
<td>Offline: extensive language test battery fMRI: Simon &amp; numeric Stroop tasks DTI: white matter (WM) brain structure</td>
</tr>
<tr>
<td>(T1)</td>
<td>2012</td>
<td>40 children (mean age = 11 years)</td>
<td>Offline: one- &amp; two-language verbal fl., Attention Network Test (ANT) fMRI: Simon &amp; numeric Stroop tasks</td>
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<tr>
<td>Cross-sectional study I (2011)</td>
<td>2011</td>
<td>17 highly proficient bilingual young adults (mean age = 24 years; 8 interpreters &amp; 9 simultaneous bilinguals)</td>
<td>DTI: WM brain structure</td>
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<tr>
<td>Cross-sectional study II (2012)</td>
<td>2012</td>
<td>25 highly proficient bilingual young adults (mean age = 21 years; 13 simultaneous &amp; 12 sequential bilinguals)</td>
<td>Offline: language test battery fMRI: two-language semantic categorization task &amp; Simon task</td>
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Table 0.2 Overview of three studies reported in this dissertation.

All different dependent variables used in the three studies that are reported in this dissertation (see Table 0.2) can be grouped into three main categories: behavioural and neural correlates of tests of language control, of cognitive control, and measurements of neural structure. Instead of reporting each study in a separate chapter, each part of this dissertation will be devoted to one of these three main categories. Bundling together data reports from the same category makes it possible to write a proper introduction to each set of tasks without having to repeat different aspects of the theoretical background in each part.

Functional plasticity in the bilingual brain and its behavioural correlates are discussed in Parts One and Two of this dissertation. Structural plasticity is the topic of Part Three. Each of these three parts is composed of three chapters: Theory & literature review (chapter 1), Data report (chapter 2) and General conclusion (chapter 3).

Part One deals with the behavioural and neural correlates of language control in bilinguals. The theoretical section of this part is composed of three major parts. First, the components of a proposed neural language control network will be elaborated. Then, two different language costs that
supposedly rely on this network will be discussed: the neural L2 cost and the mixed-language cost. Next, this part will report data from the language test batteries that were collected at T1 & T2 of the longitudinal study and cross-sectional study II. In addition, the behavioural and neural correlates of a two-language semantic categorization task that was part of the same experiment will be reported. This part will show how different aspects of bilingual language use, such as language switching, mixing and L2 processing, tap into varying components of the language control network.

**Part Two** uncovers the behavioural and neural correlates of cognitive control in bilinguals. First, the theoretical foundations for assuming bilingual effects on cognitive processing are provided, together with a discussion of the large amount of studies contradicting each other on the existence of a bilingual advantage. Then, the behavioural and neural data from the Simon & numeric Stroop task at T1 & T2 of the longitudinal study will be dealt with, in addition to the behavioural data from the ANT at T2 and the behavioural and neural data from the Simon task in cross-sectional study II. The connection with the previous part will be made clear by correlation analyses between measures of language control described in Part One and measures of cognitive control described in Part Two.

**Part Three** turns the focus of attention to structural plasticity in the bilingual brain. After a theoretical introduction to this topic, data from two DTI scans are discussed, more specifically at T1 of the longitudinal study and cross-sectional study I.

Finally, **Part Four** presents a combined psycho- and sociolinguistic theory of controlled processing in bilinguals. Data from all three studies of this dissertation will be combined with the extant literature on the topic to explain contradictory results in previous studies and to provide a general framework for understanding what type of bilingualism makes individuals smarter.
Part One
Neural and behavioural correlates of language control in bilinguals
One of the most striking features of human’s language processing is the ability to accommodate two or more languages in one brain. This increases the linguistic flexibility because it allows a bilingual to adapt to a wider range of communicative situations than monolinguals. In addition to just speaking one language to a monolingual speaker, bilinguals can communicate subtleties with other bilingual speakers by selectively using one of their languages or by switching between their two languages (see, for an overview, Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2011). Even though this rich linguistic repertoire may be seen as an added value, code switching is often a stigmatized sociolinguistic marker (Poplack, 1980, for a description of the situation in Brussels, see Treffers-Daller, 1992).

Many examples of language environments can be given to illustrate this linguistic flexibility. In a description of bilingual discourse in Swedish-English bilinguals in the United States, for example, Hasselmo (1970) mentioned three different modes of speaking: English for interactions with US natives; American Swedish with some bilinguals (English as dominant language) and Swedish American with others (Swedish as dominant language). The first mode can be characterized as one- or single-language processing, whereas the second and third modes are instances of two- or mixed-language processing. As a consequence, bilinguals need a cognitive apparatus, both to monitor what language mode has to be used and to keep two language systems available during two-language processing. The processes that subserve these skills are referred to as controlled language processing (or language control).

A crucial question in this part is in what type of bilingual discourse bilinguals will rely most on controlled processing. Even though it seems intuitive to propose that mixed-language processing requires more control than single-language processing, early accounts of language control in the bilingual mind seemed to indicate rather the opposite. Weinreich (1966), for example, stated that bilinguals will have to exert more rather than less control over their language use when speaking to monolinguals. During single-language processing, it was argued, bilinguals have to suppress potential interference from the language not understood by the interlocutor. Two-language processing would not entail this constraint as
bilinguals could then freely interact without the need to suppress interference (Baetens-Beardsmore, 1982).

Grosjean’s Language Mode hypothesis (1997) offers an interesting framework for understanding control requirements in bilingual speech. According to this theory, a language mode can be defined as a communicative context that determines the state of activation of each of a bilingual’s languages. Each of these contexts can be visualized as a point on a continuum (see Figure 1.1). In the purely monolingual mode, only one of the languages is active with the other one completely deactivated, which implies that no sustained controlled language processing is needed. In the bilingual mode, both languages are supposed to be activated and language control is required to tear them apart.

Dijkstra & van Hell (2003) tested the Language Mode hypothesis in a laboratory context with bilingual and monolingual participants. Isolated words were presented in single-language and mixed-language lexical decision tasks. Some of these words were cognates. These are words from different languages that have the same phonological or orthographic features but a different meaning (e.g., the Dutch word ‘boom’ means ‘tree’ in English). Evidently, the difference between cognates and non-cognates is only relevant for bilinguals. If the Language Mode hypothesis is true, it was argued, bilinguals have the ability to turn off the other-language meaning of the word as long as they are placed in a purely single-language context. However, this did not turn out to be the case. Cognates were processed more slowly than control words, as well in mixed-language as in single-language contexts.

Controlled language processing thus seems to be needed in both aspects of bilingual language processing. Indeed, bilinguals not only have to suppress interference in situations where the two languages have to be kept available simultaneously, such as during translation, interpreting or code switching, but also when they are in the monolingual mode, for example while communicating in a less proficient language (see, for an overview of studies, Abutalebi, 2008).
Corresponding to these two aspects, the behavioural and neural effects of controlled language processing can be investigated from two different perspectives. One first possibility is to look at the neural L2 cost. This refers to the additional neural resources that are recruited to implement two processes involved in the processing of a less proficient language: the inhibition of the dominant language and the activation of the less proficient one (Abutalebi, 2008). A second perspective is the study of mixed-language costs. Similar to the activation of a less proficient language, the simultaneous use of two language systems results in the use of additional neural networks and it incurs a behavioural cost (Grainger & Beauvillain, 1987).

This part will systematically deal with each of these two language control costs in the chapter entitled ‘Theory & literature review’. This first chapter starts off with a description of the neural language control network. In the second chapter, data will be reported from a longitudinal study with bilingual children and from cross-sectional study II with bilingual young adults. This part will end with a ‘General conclusion’ (chapter 3).
Chapter 1
Theory & literature review

1. A neural network of language control

The increasing use of neuroimaging in healthy populations has gradually led to the emergence of a new view on language processing. Previously, a main distinction in neural correlates of language processing was made between language comprehension and production. According to the Wernicke-Geschwind model, each of these functions is subserved by different language centres in the brain: Wernicke’s area is supposed to underlie speech comprehension, whereas Broca’s area is responsible for language output (Geschwind, 1970). Recent neurolinguistic research has challenged this view by showing that Broca’s area is also implicated in speech processing (Poeppel et al., 2008) and that speaking is even possible without Broca’s area (Plaza et al., 2009). An alternative view to the Wernicke-Geschwind model posits that both Wernicke’s and Broca’s area subserve automatic (input and output) language processing, whereas other neural regions are in charge of controlled language processing.

The neural correlates of controlled processing cannot be attributed to one single region in the brain, but these processes are embedded in a composite neural network that involves the prefrontal cortex (PFC), the anterior cingulate cortex (ACC), the inferior parietal cortex and the caudate nuclei in the basal ganglia (see Figure 1.2, Braver, Reynolds, & Donaldson, 2003; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; de Zubicaray, Andrew, Zelaya, Williams, & Dumanoir, 2000). The main function of this network is to suppress interference from irrelevant information, to select relevant features for task execution and to inhibit non-target responses (Bunge et al., 2002). These processes are thought not to be specifically engaged in one type of controlled processing, such as language control, but to serve domain-general purposes. The contribution of each of the components to the language control network is discussed in the following paragraphs.
1.1 Lateral parts of the prefrontal cortex

The PFC is the most anterior part of the cerebral cortex. It is situated in front of the motor and premotor areas of the frontal lobe. Theoretical models of prefrontal cortex functioning have repeatedly highlighted its engagement in executive functioning or cognitive control (Goldman-Rakic, 1988; Miller & Cohen, 2001). This control function is made possible by its structural interrelatedness to almost all sensory, motor, and associative neocortical systems and to a wide range of subcortical structures (Miller, 1999). It is not easy to connect particular subregions of the PFC to specific control functions (Elliott, 2003), yet the lateral portions of the PFC are expected to have a role in working memory, planning and sequencing of behavior, language and attention (Abutalebi & Green, 2007). The overarching function of this part of the PFC is to subserve top-down bias mechanisms that facilitate task execution in the face of interfering information (Dehaene & Changeux, 1991).

Petrides (1998) proposed a two-level distinction between the dorsolateral (BA 9 & 46) and ventrolateral parts (BA 45 & 47) of the PFC. The dorsolateral areas are responsible for sequential processing and self-monitoring, whereas the ventrolateral areas are engaged in controlled retrieval of information from posterior neural regions. Automatic retrieval processes, in contrast, would not require PFC involvement. Hence, PFC involvement is expected in non-automatized tasks, such as the processing of a less proficient language. Other functions of the left ventro- and dorsolateral PFC relate to response selection (Pochon et al., 2001), and the resolution of interference (D’Esposito et al., 1995; Jonides, Smith, Marshuetz, & Koeppe, 1998). Right PFC activity was reported during the inhibition of an inappropriate response (Aron, Robbins, & Poldrack, 2004).

Cognitive control also requires selection processes to ensure appropriate task execution in the face of competing alternatives. A neural network composed of the PFC and the inferior parietal cortex might be implicated in the selection of competing responses (Petrides & Pandya, 1984; Schwartz & Goldman-Rakic, 1984; Abutalebi & Green, 2007). A dissociation has been proposed between the two components of this network: while the left parietal cortex is only involved in maintaining a representation among possible responses, the PFC is crucially involved in the selection of the target response. The crucial involvement of the PFC in selection mechanism
has been confirmed in the domain of language processing (Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D’Esposito, & Kan, 1999). The extent of prefrontal activity in language tasks was found to be dependent on the number of competing alternatives in semantic memory with more competing alternatives to the target word triggering activity in a larger left prefrontal network (Thompson-Schill et al., 1997). Functional PFC plasticity was also reported as a function of task practice. After participants had gained experience in the task, less activity was found in the PFC (Thompson-Schill et al., 1999).

Figure 1.2 The components and functions of the neural language control network. Source: Abutalebi & Green (2007, p. 249).
1.2 Anterior cingulate cortex
The anterior cingulate cortex is the frontal part of the cingulate cortex, a medial neural region that surrounds the corpus callosum. Activity in this region has been found in a wide range of executive functioning tasks (Cabeza & Nyberg, 1997) such as during conflict trials of interference tasks (Pardo, Pardo, Janer, & Raichle, 1990).

Functionally, the ACC has been linked to error detection (Bush, Luu, & Posner, 2000) and conflict monitoring (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). This implies that this region evaluates the need of cognitive control by monitoring for the occurrence of conflict or interference in the processing of two stimuli or responses (Carter et al., 2000; Botvinick et al., 1999).

Most executive functioning tasks appear to co-activate the PFC and the ACC (Duncan & Owen, 2000). Hence, studies have been designed to isolate the distinct roles of each of these neural correlates of cognitive control. One theory states that the ACC functions as a conflict detector while the dorsolateral part of the PFC implements control by modulating activity in posterior cerebral and subcortical regions (Botvinick, Cohen, & Carter, 2004; MacDonald, Cohen, Stenger, & Carter, 2000).

One interesting example of the importance of this network for controlled language processing can be found in the neural correlates of tip-of-the-tongue states. This phenomenon refers to the failure to retrieve a known word from semantic memory (Brown, 1991). This conflict between the conviction of knowing the word and the failure to retrieve it leads to co-activation of the ACC and the lateral parts of the PFC (Maril, Wagner, & Schacter, 2001).

1.3 Basal ganglia
The basal ganglia are formed by a group of nuclei that are located deep under the cerebral cortex. They are strongly connected with the cerebral cortex, most notably the PFC, the thalamus, and other brain areas. Traditionally, the basal ganglia are associated to motor control because a lesion to these structures results in dysfunction of movement, such as in Parkinson’s and Huntington’s disease (Cameron, Watanabe, Pari, & Munoz, 2010; Walker, 2007). Only recently, the function of the basal ganglia has
been extended to include cognitive control. Graybiel (1997) pinpoints cognitive sequence planning as a critical function of the basal ganglia.

Impairments to the basal ganglia also lead to deficits in language processing. Abutalebi, Miozzo and Cappa (2000) reported the case of a trilingual patient with a lesion to the white matter surrounding the head of the left caudate. Even though comprehension was preserved in all of her languages, she switched spontaneously and involuntarily between her languages during production tasks. This suggests that the basal ganglia are critically involved in the suppression of non-target lexical alternatives, a function that is possibly subserved by a neural circuitry that also includes the PFC. Indeed, impairments to the basal ganglia in monolinguals disrupt the suppression of competing alternatives in production tasks (Friederici, Rüschemeyer, Hahne, & Fiebach, 2003).

Within the basal ganglia, a distinction can be made between the caudate nucleus and the putamen as to their involvement in motor control of language and language, respectively. Robles, Gatignol, Capelle, Mitchell and Duffau (2005) used intraoperative direct electrical stimulation to investigate this issue. Stimulation to the caudate nucleus led to perseveration in picture naming, which might be indicative of a language control disorder. In contrast, stimulation of the putamen resulted in dysarthria, a motor speech disorder.

1.4 Bilingual neural overlap

The main topic of this dissertation is the link between bilingualism and cognitive processing. The issue of control figures prominently in these discussions because a certain degree of overlap is expected between regions that subserve general-purpose and language-specific controlled processing. Indeed, the regions that are part of the language control network also contribute to controlled processing, in general. The use and stimulation of these regions in bilingual speech might induce functional plasticity and, as a result, underlie bilingual effects on cognitive control. Therefore, the following questions will receive most attention in this chapter. First, during what bilingual language activities do bilinguals rely most on controlled processing? Second, what are the bilingualism-related factors that contribute to the variability in the reliance on controlled processing?
2. Neural correlates of the L2 cost

2.1 Theoretical models of the L2 cost

Ever since the beginning of neurological investigations into bilingualism in the nineteenth century, the question which additional neural resources are required to accomplish mastery of a second language has received much attention (Scoresby-Jackson, 1867). In general, two conflicting views on how a second language is integrated at a neural level can be distinguished: the Differential Representation hypothesis and the Neural Convergence hypothesis (Green, 2003).

The Differential Representation hypothesis predicts that the neural L2 cost can be clearly defined in neuroanatomical terms. A strong version of the Differential Representation hypothesis states that a second language will be subserved by the right hemisphere (Albert & Obler, 1978). This is different from the localization of the native tongue, which is in more than 90% of all right-handed individuals lateralized to the left hemisphere (Loring et al., 1990; Springer et al., 1999). The strong version of the Differential Representation hypothesis was rejected by studies on right-handed bilingual aphasics, who showed no higher incidence of aphasia after right-hemisphere lesions than monolinguals (Fabbro, 1999).

The following section discusses two models that can figure as two recent instances of the Differential Representation and Neural Convergence hypotheses. The first model that will be discussed is the Declarative/Procedural (D/P) model of language processing (Ullman, 2001). Embracing a weak version of the Differential Representation hypothesis, it emphasizes age-related effects on the neural localization of L2 processing. In contrast, the Neural Convergence hypothesis (Green, 2003), proposes a more proficiency-driven and dynamic perspective on neural L2 processing.

2.1.1 Declarative/Procedural model (D/P)

Model description. This model starts from a fundamental distinction between two key components of language processing: a mental lexicon composed of memorized words, and a mental grammar made up of internalized rules. These two different language subsystems are related to
the distinction between declarative or explicit and procedural or implicit long-term memory systems (Paradis, 2004; Ullman, 2001). Whereas the declarative or explicit memory system underlies the processing, storage and use of lexical information, the implicit or procedural memory subserves the same aspects of grammatical knowledge. These two memory systems differ from each other in that only explicitly stored memories, such as facts and knowledge, can be consciously recalled.

The neural correlates of these two memory systems are well known (Squire, 2004). The declarative memory system is subserved by medial temporal lobe regions, including the hippocampal and parahippocampal gyri. On the opposite, the procedural memory system is embedded in a network involving the frontal lobe and the basal ganglia. Interestingly, the proposed model predicts a certain degree of convergence in the neural localization of both systems: once the procedures have been learned (or automatized), they are stored in temperoparietal regions.

Based on the extensive literature on a biologically-defined sensitivity of linguistic abilities to the age of acquisition (Johnson & Newport, 1989), the D/P model predicts age-related effects on the neural representation of second language processing. Most notably, grammatical processing is thought to be more affected by age effects than lexical abilities (Birdsong, 1999). This higher sensitivity to age is held to be responsible for a shift in the type of memory system that underlies L2 grammatical processing. Whereas the grammar of an early acquired second language is embedded in neural circuitry subserving procedural memory, the L2 grammar of late learners would be represented in a declarative memory system.

Evaluation of the model. One of the strong points of this model resides in the fact that it exceeds the traditional boundaries of domain-specific linguistic theory by providing a clear link between linguistic (mental lexicon and grammar) and non-linguistic functions (domain-general long-term memory) in the human mind. However, this non-modular approach is not extended to different levels of language processing. Contrary to connectionist models that fuse lexical and grammatical information into a single-mechanism theory (Rumelhart & McClelland, 1986), the D/P model sticks to a traditional dual-mechanism theory of language processing with functionally and structurally distinct correlates for each of its two components.
Crucial to this model is the existence of critical time frames during which a certain skill has to be acquired. Such a critical period was first hypothesized for first language acquisition and it refers to the observation that successful language development is only possible when an individual is exposed to language before puberty (Lenneberg, 1967). This idea was later extended to include second language acquisition, predicting that certain language abilities will not reach a native-like level if the onset of second language exposure occurs after puberty (Birdsong, 1999). However, there is no conclusive evidence for age effects on any level of linguistic analysis, including those that are typically referred to in favour of a critical period, such as accent (see Bongaerts, Planken, & Schils, 1995). Even though some studies seem to indicate that children learn languages with greater ease than adults (Flege, Munro, & MacKay, 1995; Weber-Fox & Neville, 1996), others have defended the idea that adult learners are more efficient language learners than children (Singleton, 1989). In fact, differences in the ease of language learning that correlate with age of exposure can as well be attributed to confounding factors such as social environment or education (Bialystok & Hakuta, 1999).

Furthermore, it should be noted that differences in age effects on explicit or implicit storage of second language grammar can easily be confounded with the manner of second language acquisition. On average, children are prone to acquire a second language in an implicit way (Lichtman, 2013). It might be that differences in how adult and child learners of a second language merely reflect these varying contexts of acquisition instead of biologically defined age-related differences.

Finally, it would be tempting to relate the D/P model to the distinction between automatic and controlled language processing. Indeed, only declarative knowledge can be consciously recalled. However, the model argues that once procedural knowledge is automatized, it is stored in the same regions that subserve declarative knowledge. Besides, the proposed neural locus of declarative knowledge cannot be related to any of the components of the neural language control network.
2.1.2 Neural Convergence hypothesis (NC)

Model description. The term neural convergence carries with it a dynamic conception of how our brain deals with newly acquired languages. In contrast to the D/P model, it offers a purely proficiency-based account of the neural correlates of a second language (Green, 2003). The NC hypothesis states that neural representations of a first and a second language will converge as a function of L2 proficiency increases. Consequently, the NC hypothesis predicts that neural L2 costs for balanced bilinguals with equal proficiency in both languages will be minimal, regardless of the onset age of exposure.

The Neural Convergence hypothesis is based on the communality assumption of neural processing (Green, 2003), which states that human brains have many features in common. Neural regions that are specialized in specific aspects of language processing, such as communicating meaning, are shared across speakers of different languages. When a second language is added to a brain that already contains regions specialized for different aspects of language proficiency, the most efficient solution is to use the same regions for L2 processing.

Evaluation of the model. The NC hypothesis offers a radically different perspective on the nature of neural L2 costs. The level of attained proficiency and not onset age of acquisition is believed to be the key indicator of neural representation, which provides a more dynamic account of neural second language representation. However, the model gives little information about the nature of the proficiency-related changes in neural L2 representation. In contrast to the D/P model, the NC hypothesis does not make clear predictions about what neural regions will show variability between speakers with different levels of proficiency.

A solution to this problem was given by Abutalebi (2008), who suggests the PFC as a possible locus for the representation of low-proficient languages in the bilingual brain. Activity in the PFC is not assumed to reflect language processing itself. It would be rather paradoxical to assume that a less proficient language requires more instead of less language-related neural activity. Rather, activity in PFC is suggested to be indicative of the higher cognitive effort involved in processing a less proficient language. Whereas the native language only relies on automatic language processing, a less
proficient language will activate regions involved in controlled language processing. Abutalebi’s extension of the NC hypothesis thus suggests that the degree of activity in language control regions is indexed by second-language proficiency: the more L2 proficient an individual becomes, the less activity will be observed in the neural language control network.

2.2 Hemodynamic functional neuroimaging evidence

This section discusses hemodynamic functional neuroimaging studies that have tested the predictions made by these two models. Two questions will receive specific attention. First, which bilingualism-related variable determines the neural L2 cost? The D/P model predicts that age will determine the neural locus of L2 grammatical processing, whereas the NC hypothesis proposes proficiency-related changes. The second question relates to the nature of the L2 cost. Abutalebi’s (2008) extension of the NC hypothesis suggested a proficiency-related decrease in reliance on controlled processing regions (see section 1.1), whereas Ullman (2001) predicts an age-related recruitment of a declarative network for L2 grammatical processing. These questions will be answered for each of the language proficiencies separately.

2.2.1 Listening or auditory L2 processing

Language-specific listening proficiency is embedded in the region of Wernicke, located in the temporal cortex of the dominant hemisphere of the cerebral cortex (see Figure 1.3). More specifically, the region of Wernicke can be found in the posterior section of the superior temporal gyrus (STG; Bogen & Bogen, 1976). Wernicke’s area is one of the two areas classically linked to language processing. It is located around the Sylvian sulcus, which explains why it is one of the perisylvian regions. A lesion to this region results in impaired speech comprehension, but preserved, though meaningless speech production. This type of receptive aphasia is called Wernicke’s aphasia (Dronkers, Redfern, & Knight, 2000).

The first empirical data on listening proficiency in bi- and multilinguals were collected using positron emission tomography (PET), a neuroimaging technique which has currently run out of fashion with healthy participants because it involves exposure to ionizing radiation (Brix et al., 2005). Using this technique, Perani et al. (1996) investigated auditory story processing in native speakers of Italian who had started learning English around age
seven and who had attained moderate proficiency in that language. Neural processing of stories in L1 compared to English and Japanese led to increased engagement of the bilateral temporal poles and the left-hemispheric temperoparietal cortex and inferior frontal gyrus. Remarkably, no additional regions were active when listening to the second language.

Dehaene et al. (1997) complemented these findings by showing differences in hemispheric lateralization between bilinguals' first and second language. The participants to this study were native speakers of French who had started acquisition of English after age seven. L1 processing led to consistent activity in the superior temporal sulcus, extending into adjacent superior and middle temporal gyri, into the temporal pole and the angular gyrus. Just as in Perani et al. (1996), L2 processing activated a lower amount of voxels. In addition, the dominance of the left hemisphere was much less pronounced when listening to L2 than to L1 speech. Interestingly, individual analyses revealed that some participants additionally recruited the inferior PFC and the ACC for processing L2 speech, both of which are components of the neural language control network.

An obvious drawback of these two studies is that they confounded onset age of acquisition and proficiency by examining late bilinguals with low L2 proficiency. In order to disentangle these two variables, Perani et al. (1998) investigated language processing in two groups of highly proficient bilingual young adults with early and late ages of acquisition.

L1 and L2 story listening activated similar regions in the two highly proficient groups. Activated clusters extended from the left-hemispheric superior temporal sulcus to the temporal pole, the middle temporal gyri and the bilateral hippocampal structures. Within-group analyses contrasting L1 to L2 processing in both directions did not show any differences. The results corroborate the assumption that a second language may still become accommodated to L1 processing regions even when it is learnt at a later age. Even though age of acquisition and proficiency are generally negatively correlated in bilingual populations (Johnson & Newport, 1989), this does not mean that acquiring a second language later in life unconditionally hampers equal efficiency in neural L2 processing. Indeed, two groups of high proficient bilinguals activated the same neural regions for L1 and L2 processing, despite differences in proficiency.
Figure 1.3 Main regions involved in language processing with Brodmann areas and anatomical description. Source: Démonet et al. (2005, p. 63).
Rueschemeyer, Fiebach, Kempe and Friederici (2005) investigated listening proficiency in German-speaking monolinguals and German-Russian bilinguals by exposing them to spoken sentences that contained semantic or syntactic violations. The processing of syntactic violations in native speakers led to additional recruitment of the bilateral STG. No additional activity was found for the same contrast in non-native speakers of German. In contrast, both native and non-native speakers activated the left IFG (Broca’s area) for semantic processing. Again, the group of native speakers showed more rather than less activity, more specifically in the right IFG. Interestingly, the contrast of brain activity for non-native speakers compared to natives across all conditions revealed additional activity in the bilateral heads of the caudate nucleus.

Saur et al. (2008) manipulated L1 and L2 word order processing requirements in sentences that were orally presented to German-French early and late bilinguals. Whereas the group of early polyglots did not show any neural differences between the two languages, the late bilinguals showed a neural L2 cost in the left inferior PFC. The localization of this neural cost was attributed to the increased structural complexity of word order processing in a non-native tongue.

To summarize, second language listening proficiency in a less proficient language seems to result in less activity in L1-related posterior processing regions, but additional activity in anterior networks, possibly supplemented by activation of the non-dominant hemisphere (Dehaene et al., 1997). Lower proficiency in a second language is possibly compensated by the additional recruitment of neural regions related to controlled processing. There is no consensus on the location of this neural L2 cost (compare Perani et al., 1996, Rueschemeyer et al., 2005 and Saur et al., 2008).
2.2.2 Speaking

Speaking proficiency is traditionally linked to the posterior part of the inferior frontal gyrus (IFG) in the dominant hemisphere. This region is also called Broca’s area. Pierre Paul Broca was the first physician to establish the relationship between speech production and this region in Leborgne, one of his aphasics (see, for a historical overview, Dronkers, Plaisant, Iba-Zizen, & Cabanis, 2007). Ever since, Broca’s aphasia is characterized by non-fluent speech in spite of preserved speech comprehension (Goodglass & Geschwind, 1976).

Recently, the crucial importance of Broca’s area for speaking has been challenged. First, neuroimaging of the brains of Broca’s patients has
revealed that their lesions were not limited to Broca’s area (Dronkers et al., 2007). This means that the speech arrest in Broca’s patients was probably not exclusively caused by an impairment to the frontal lobe. Second, clinical cases have demonstrated that speaking without Broca’s area is possible. In one patient, the left IFG was destroyed after tumour resection. However, only minimal language problems, such as impaired syntactic complexity, were attested three months after surgery (Plaza et al., 2009). Experimental studies have led to similar results: Etard et al. (2000) proposed a ‘direct pathway’ for naming proficiency, without involvement of Broca’s area. This was confirmed by Wise, Greene, Buchel and Scott (1999) who did not track IFG activity during a speech output task. In addition to Broca’s area, speaking proficiency activates the left insular cortex, which is folded deep within the Sylvian sulcus, and the left basal temporal areas (Démonet, Cardebat, & Thierry, 2005).

The first information about the neural localization of speaking in a second language came from PET scans during word repetition in L1 and L2 (Klein, Zatorre, Milner, Meyer, & Evans, 1994). Between-language comparisons revealed additional activity in the left putamen, one of the structures that form the basal ganglia. This was related to motor control needed for speaking a second language. The importance of the left putamen was recently confirmed by an event-related functional MRI study in multilinguals (Abutalebi et al., 2013a). Interestingly, increased activation during non-native speech production was only found for the language in which the trilingual participants were least proficient.

In a follow-up study by the same research group (Klein, Milner, Zatorre, Meyer, & Evans, 1995), the English-French bilingual volunteers saw single words in the two languages and had to pronounce synonyms (semantic retrieval) or rhyme words (phonological retrieval). Irrespective of the language involved or of the retrieval type, the tasks appeared to activate similar regions in the left-hemispheric IFG and the adjacent dorsolateral PFC.

Yetkin, Yetkin, Haughton and Cox (1996) used fMRI to localize activated areas during speech processing in three languages. Left IFG activity was found in all participants. Unlike in language reception tasks, the number of activated voxels was highest for the language in which the person was least fluent. Additional active regions for L2 processing were also found by
Vingerhoets et al. (2003) in a study of word fluency and picture naming in Belgium-born native speakers of Dutch who had started acquisition of French and English at school after age ten. A neural L2 cost was found for word generation in the bilateral IFG, including Broca’s area, and in the left middle temporal gyrus. Picture naming led to neural L2 and L3 costs in the inferior and medial frontal regions, predominantly lateralized to the left hemisphere.

Kim, Relkin, Lee and Hirsch (1997) compared two groups of early and late bilinguals on the extent of activity generated by a speech production task in Broca’s area. Age-related group differences were found in the degree of overlap between the neural representation of L1 and L2. In contrast to the early bilinguals, the late bilinguals did not recruit any common voxels in Broca’s area for L1 and L2 (see Figure 1.4). In addition, the distance between the central points of significantly activated clusters for L1 and L2 was smaller in early than in late bilinguals. These results were not confirmed by Chee, Tan and Thiel (1999) in a study with Chinese-English bilinguals. Again, two groups were distinguished: early bilinguals had acquired English before age six and the late bilinguals had started acquisition after age twelve. All participants performed a word generation task during which they had to complete a word stem being presented as a cue in one of the two languages. Statistical analyses could not detect any significant between-language or between-group differences. Similar results were seen with verb generation, both in blocked (Klein, Milner, Zatorre, Zhao, & Nikelski, 1999) and in event-related designs (Pu et al., 2001).

A potentially confounding variable that might explain contradictory results is the amount of exposure to each of the languages involved. Perani et al. (2003) investigated brain activity in two groups of Spanish-Catalan bilinguals during a verbal fluency task. Both groups acquired their second language in early childhood and language tests revealed no proficiency differences. The crucial difference between the two groups was their exposure to the second language with native speakers of Spanish being more exposed to Catalan than native speaker of Catalan to Spanish. Within-group analyses contrasting L2 to L1 revealed distinct neural L2 costs for the two groups. Both groups recruited additional inferior and middle frontal areas for verbal fluency in their second language. Only Catalan-born bilinguals also recruited bilateral portions of the IFG, the inferior parietal
and premotor cortices and the left caudate nucleus. A between-group analysis contrasting the two groups revealed additional activity for the Catalan-born group in the left inferior parietal lobule and the middle frontal gyrus. Exposure, thus, turned out to be a relevant factor that determines the extent of the neural L2 cost, even after controlling for proficiency and age of acquisition. Interestingly, lower amounts of exposure to L2 result in recruitment of a language control region (the left caudate nucleus), even for a fairly simple task as verbal fluency.

To summarize, speaking a second language seems to activate additional regions in a network that encompasses the frontal cortex and the basal ganglia (putamen and caudate nucleus). The variables that have an impact on the presence of additional activity and its extent are the onset age of acquisition (Kim et al., 1997), the attained level of proficiency (Chee et al., 1999), and the amount of exposure (Perani et al., 2003). However, after controlling for the other factors, only proficiency and exposure result in neural differences.

### 2.2.3 Reading or visual L2 processing

Reading proficiency relies on visual processing in the occipital cortex. There has been much debate on the language-specificity of a proposed Visual Word Form Area in the middle portion of the left fusiform or occipitotemporal gyrus (Dehaene & Cohen, 2011). The existence of a region specifically involved in the visual processing of linguistic material has recently been refuted (Price & Devlin, 2003). It can be argued that reading proficiency is a relatively recent phenomenon from evolutionary perspective. Therefore, it turns out to be very unlikely that the human brain developed a specific neuroanatomical correlate for this skill.

Illes et al. (1999) investigated the neural correlates of L1 and L2 semantic processing in late English-Spanish bilinguals. Participants had to decide whether visually presented words referred to abstract or concrete entities. A reliable pattern of neural activity during L1 and L2 was found in the classical language areas of Broca and Wernicke in the dominant hemisphere. Interestingly, direct comparisons did not elicit any differences between L1 and L2.
Chee, Hon, Ling Lee and Soon (2001) compared two groups of Mandarin-English bilinguals from two language backgrounds, each with a different dominant language. Both groups showed recruitment of additional bundles of neurons in the middle and IFG and the ACC in the left hemisphere for their non-dominant languages. Additionally, an intricate link was found between activity in the left PFC and temporal areas and lower proficiency. A later study with Chinese-dominant L2 speakers of English elaborated on these findings by showing that also activity in right-hemispheric regions might compensate for lower proficiency (Ding et al., 2003).

The use of similar brain regions for representing L1 and L2 semantics is not surprising. The Differential Representation hypothesis predicts age-related different patterns of neural activity for syntactic and not for semantic processing. According to the D/P model, early bilinguals are expected to rely on a procedural, native-like neural network that involves the frontal cortex and the basal ganglia for L2 grammatical processing. In contrast, late bilinguals are thought to recruit a declarative network in posterior brain regions (Ullman, 2001).

This hypothesis was tested in a study of Chinese-born late learners of English (Luke, Liu, Wai, Wan, & Tan, 2002). Overlapping brain activity for L1 and L2 was found with peak activity in the left middle frontal gyrus. The integration of a later learned grammar into L1 grammatical processing networks conflicts with the idea of a Differential Representation hypothesis for L2 grammatical processing as proposed by the D/P model.

However, only a direct comparison between late and early bilinguals can assess the existence of age-related effects in neural grammatical processing. Using a study design intended to disentangle age- and proficiency-related effects, Wartenburger et al. (2003) divided a population of German-Italian bilinguals into three different groups based on their ages of acquisition and their results on a language test: early balanced, late balanced and late non-balanced bilinguals. The most important result of this study was that all late bilinguals, irrespective of their language proficiency, showed a neural L2 grammar cost. Whereas early bilinguals did not recruit additional regions for L2 grammatical processing, late and balanced bilinguals recruited a neural network with activation peaks in bilateral middle and IFG extending into the anterior insula and in the left inferior parietal lobule. A direct comparison between the three groups only
showed additional activity for late bilinguals, more specifically in the bilateral IFG (see Figure 1.5).

This study partly confirmed an age-based account of Differential Representation for L1 and L2. Even though semantic and syntactic proficiency as measured by traditional language tests was equal for the early and late high-proficient bilinguals, the neural cost of representing a second language was only visible in the late bilinguals and it was restricted to grammatical processing. In contrast to the predictions of the D/P model, however, the neural cost did not correspond to the recruitment of posterior neural regions, but to additional activity in native language processing areas (the left IFG).

Interestingly, a later study with adolescent Japanese-speaking learners of English provided evidence for a proficiency-based account of differences in left IFG activity. Tatsuno & Sakai (2005) reported additional activation of the left IFG during L2 grammar processing in a group of low-proficient language learners compared to high-proficient learners who were matched for age of acquisition and length of exposure.

The capacity to recruit L1-related neural regions for processing grammar in a language learned later in life may challenge the critical period hypothesis, and that is even more so if the new language is learnt after puberty. Indefrey, Hellwig, Davidson, & Gullberg (2005) conducted a longitudinal study with international Chinese students in Holland, who had never before been in touch with the Dutch language. Three, six and nine months after their arrival, participants were asked to produce grammaticality judgements on Dutch sentences in an MRI scanner. After six months already, native-like hemodynamic responses were found in Broca’s area.

To conclude, both studies on L2 grammatical and semantic processing show similar results: either there is no neural L2 cost (Illes et al., 1999) or there is a cost that can be localized in the left IFG. Moreover, both for semantic and grammatical processing, a direct correlation was found between activity in the IFG and lower proficiency (Chee et al., 2001; Tatsuno & Sakai, 2005). This refutes the D/P model which predicted different neural representations for semantic and grammatical processing. Also a purely proficiency-based account of L2 processing, as suggested by
the NC hypothesis, can be refuted. Wartenburger et al. (2003) found age-related differences in the IFG, even after controlling for proficiency.

![Figure 1.5 Functional plasticity in L2 grammatical proficiency according to age of acquisition](image)

Figure 1.5 Functional plasticity in L2 grammatical proficiency according to age of acquisition. Sagittal (top) and axial (bottom) slices of early and high-proficient (left), late and high-proficient (middle) and late and low-proficient (right) bilinguals during execution of an L2 grammatical judgement task. Note the differences between high-proficient early and late bilinguals. Source: Wartenburger et al. (2003, p. 165).

3. Behavioural and neural correlates of mixed-language processing

Mixed-language processing refers to language activities during which bilinguals have to process two languages at the same time, a skill with extensive language control requirements. The most logical way to test this is in the bilingual mode (Grosjean, 1997), such as during language switching or translation. But even in the monolingual mode, bilinguals might unconsciously process their two languages. A review of studies comparing L1 and L2 processing across different populations and proficiencies has revealed that bilinguals do not use different neural networks for representing linguistic material in their two languages (see
previous section). Logically, this leads to possible interference between the two language systems. Indeed, interference tasks with stimuli that show a certain degree of overlap with features from the other language, have revealed simultaneous activation of the two languages on a wide variety of single-language tasks (see, for an overview, van Heuven & Dijkstra, 2010).

Traditionally, interference tasks are composed of stimuli with specific features that are shared by several language systems. Depending on whether these stimuli are mapped to the same response or to different responses in each of the languages involved, they may facilitate or inhibit linguistic processing in bilinguals. Thus, (quasi-)identical stimuli with similar meanings in different languages, such as cognates (e.g. ‘name’ and ‘naam’ in English and Dutch, respectively), will be processed more quickly by a bilingual than by a monolingual (Caramazza & Brones, 1979). In contrast, words in language A that look or sound like words in language B, but have a different meaning, such as interlingual homographs (e.g., ‘boom’ in Dutch (meaning: ‘tree’) and English, respectively), will be processed more slowly (Dijkstra, Grainger, & van Heuven, 1999).

De Bleser et al. (2003) investigated the neural correlates of native and foreign language cognate and non-cognate picture naming in Dutch-French bilinguals. Though no general differences were detected between L1 and L2 naming, additional activity was found specifically for L2 non-cognates in the left IFG and temperoparietal areas. Because of their similarity with L1, cognates can thus reduce the neural L2 cost and facilitate non-native processing in bilinguals. Van Heuven, Schriefers, Dijkstra and Hagoort (2008) investigated the neural correlates of Dutch-English interlingual homographs processing in a set of lexical decision tasks. In a general version of this task, non-words had to be rejected and real words, irrespective of their language belonging, accepted. In an English-only lexical decision task, not only the non-words but also the Dutch words had to be rejected. In both tasks, the presented words were expected to generate conflict between the Dutch and English readings of the word. Indeed, the contrast between interlingual homographs and control words revealed activity in the left PFC. The English-only condition created an additional difficulty: each of the two readings was associated to a different response. This was also reflected in the neuroimaging data by the additional activation of the ACC.
3.1 Theoretical models of mixed-language processing

Three influential theoretical models of the behavioural and neural correlates of mixed-language processing are discussed in the following section. These models are highly relevant to this dissertation because they are often referred to in studies on bilingual advantages in cognitive control (e.g., Bialystok et al., 2005b; Bialystok, Craik, & Luk, 2012; Linck, Schwieter, & Sunderman, 2012). Each of these theoretical models has its specific relevance in light of this discussion. The Revised Hierarchical model connects different language control requirements to the direction of language switches (Kroll & Stewart, 1994). Next, the Bilingual Interactive Activation (Plus) model explains why controlled language processing is an intrinsic characteristic of bilingual language use (Dijkstra & van Heuven, 1998; 2002). Last, the Inhibitory Control model describes the mechanism that is needed to implement the target language and to suppress the non-target language (Green, 1998).

3.1.1 Revised Hierarchical model (RH)

Even though the Revised Hierarchical model was proposed almost twenty years ago (Kroll & Stewart, 1994), it is still considered to be one of the leading models in explaining bilingual mixed-language processing. Besides, it still triggers much debate and controversy as indicated by the title of an article published only three years ago: ‘Is it time to leave behind the Revised Hierarchical model of bilingual language processing after 15 years of service?’ (Brysbaert & Duyck, 2010).

*Model description.* The RH model was first proposed to account for asymmetric translation performance in late and unbalanced bilinguals. In this experiment, isolated words were presented in the context of semantically related or randomized lists. Bilingual translation was slower for the semantically categorized lists, but only for translating words from the first to the second language (Kroll & Stewart, 1994).
This was explained by designing a model that distinguished between the mental representations of word forms (lexical information) with separate stores in each of the two languages, and the representation of word meaning, with one store for both languages (see Figure 1.6). Within this model, the lexical links between word forms are supposed to be stronger from L2 to L1 than from L1 to L2. In addition, L1 lexical items are assumed to have stronger links to the conceptual store than L2 lexical items. Because of the strong links between L1 lexical items and the conceptual store, translating a single word from L1 to L2 (forward translation) relies on concept-mediation. The links between L2 lexical items and the conceptual store are rather weak. Therefore, the opposite translation direction (L2 to L1 or backward translation) is assumed to be lexically mediated and semantic-independent.

*Evaluation of the model.* A crucial question regarding the RH model is whether it can be generalized to bilingualism in general. The idea that L2 lexical items are more strongly connected to L1 lexical items than to a conceptual store seems to be tightly linked to one specific form of second language acquisition: the grammar-translation method. Initially applied to the teaching of dead languages, this language teaching method is still widely used. Its contribution to the achievement of language skills is under debate. As Richards and Rogers (2001, p. 7) put it: “[T]hough it may be true that the Grammar-Translation method is still widely practiced, it has no advocates. It is a method for which there is no theory. There is no literature
that offers a rationale or justification for it or that attempts to relate it to issues in linguistics, psychology, or educational history." It speaks for itself that the manner of acquisition might have an impact on bilingual mixed-language performance and that it should therefore be controlled for in any general theory of bilingualism.

The generalizability of the RH model was empirically tested in a translation recognition task with high- and low-proficient bilinguals. Only the low-proficient group appeared to activate the L1 equivalent when accessing meaning in L2 (Sunderman & Kroll, 2006). Once learners had achieved a certain level in L2, they were not sensitive any more to words that resemble the translation. Adding a developmental factor to the model, Kroll, Michael, Tokowicz and Dufour (2002) concluded that the two directions of translation will become more similar as individuals become more proficient in their second language.

### 3.1.2 Bilingual Interactive Activation (Plus) model (BIA)

The Bilingual Interactive Activation model initially dealt with the general question how bilinguals access their mental lexicon (Dijkstra & Van Heuven, 1998), but was later updated to include predictions about contextual influences on these processes (Dijkstra & van Heuven, 2002). In contrast to the RH model (Kroll & Stewart, 1994), one of the main tenets of this model is that L1 and L2 lexical items share a common storage and that bilinguals cannot selectively access items in either of these languages. This means that the main mechanism of lexical access is the same in bilinguals and monolinguals, namely, all lexical items compete for activation. However, the presence of lexical items in more than one language brings about higher language control requirements in the bilingual mind.

**BIA: Model description.** The Bilingual Interaction Activation model (Dijkstra & Van Heuven, 1998) is an extension of the Interactive Activation model of (monolingual) language processing (McClelland & Rumelhart, 1981). This model posits three distinct levels of visual and auditory word recognition processing: a first one at the (acoustic) feature level, a second at the letter (or the phoneme) level, and a third at the word level. In practice, visual input is thought to excite detectors of visual features, which, in turn, stimulate other detectors at the letter level, and so forth. These three levels should not be kept strictly separate. Recognition is supposed to be an
interactive process with top-down and bottom-up processes operating in parallel (see Figure 1.7).

Specific to bilingual language processing is the addition of a fourth layer which is composed of language tags. Based on information from the previous layers, individuals can establish the language membership of a presented word. However, these language tags have no effect on the activation level of individual words. Rather, they operate in a post-lexical stage by inhibiting automatically activated lexical competitors with the wrong language tags. Importantly thus, the presence of language tags does
not prevent other-language lexical items from interfering with target language words.

A first line of evidence for this model was found in *neighbourhood density* studies, which investigate how lexical access of a target word is influenced by the number of similar words (Van Heuven, Dijkstra, & Grainger, 1998). Neighbouring words differ in only one feature from a target word, for example by one grapheme in visual word recognition (‘work’ and ‘cork’) or by one phoneme in auditory word recognition (‘work’ and ‘lurk’). The number of similar words is negatively related to the speed of lexical decisions (Grainger, O’Regan, Jacobs, & Segui, 1989). Van Heuven et al. (1998) investigated the language specificity of these neighbourhood effects by manipulating the number of orthographic neighbours in the same and the other language of the target words. Interestingly, increasing the number of Dutch orthographic neighbours systematically slowed down response times for English words in Dutch-English bilinguals. This result showed that non-target neighbours have a behavioural effect on target language processing, even if no explicit attention is given to that language.

A second line of evidence came from priming studies that investigate the effect of presenting an orthographically similar prime to target word reaction times. Lexical decisions on target words preceded by orthographically similar primes are faster than on target words with dissimilar primes (Segui & Grainger, 1990). For example, the prime-target combination ‘sing – ring’ yields slower decision times than the combination ‘deal – ring’. Bijeljac-Babic, Biardeau and Grainger (1997) discovered that these behavioural effects are not confined to single-language prime-target combinations. Prime and target word sets from different languages (‘ving’ [Dutch for ‘caught’, but a non-word in English] and ‘sing’) result in comparable similarity-related effects.

*BIA +: model description.* The BIA predicts that target and non-target language items will compete for activation when isolated words are presented to a bilingual, but it says nothing about the contextual influences on these processes. Therefore, the original BIA model was updated to include the effects of linguistic and non-linguistic context on lexical access in bilinguals (Van Heuven & Dijkstra, 2002). This was accomplished by separating the word identification system with its four different layers from a newly proposed decision system (see Figure 1.8). The BIA+ model
predicts that the linguistic or syntactic context of a word affects the word identification system, while the extra-linguistic context affects the task/decision system.

The effect of sentence context on word recognition was investigated by Altarriba, Kroll, Sholl and Rayner (1996) in a mixed-language task with English-Spanish highly proficient bilinguals as participants. Previous experiments had shown that semantic constraints might facilitate recognition of target words (e.g. Ehrlich & Rayner, 1981). This means that if a certain word is anticipated due to the sentence context in which it occurs, lexical access will be speeded up as compared to neutral contexts that allow for many alternative meanings. For example, access to the meaning of the target word ‘money’ will be more easily accessed in a high-constraint context such as ‘he wanted to deposit all of his money at the credit union’ than in a neutral sentence like ‘he always placed all of his money on a silver dish on the dresser’.

Crucial in a mixed-language task is the question what will happen if the target word belongs to another language, such as in the sentence ‘he wanted to deposit all of his dinero at the credit union’, in which ‘dinero’ [Spanish translation for English ‘money’] is the target word? As could be expected, inhibitory effects were found in high-constraint context, which means that these contexts anticipate a specific word form (‘money’) rather than a semantic content (‘objects accepted for payment of goods and services’, a definition which is equally met by the words ‘money’ and ‘dinero’). Critically, semantic constraint anticipates a particular word form but not a word belonging to a specific language. Indeed, no interaction was found between language membership and sentence constraint: the low-frequent Spanish target words followed the same pattern as the English ones. This suggests that lexical characteristics, such as frequency, more reliably predict word recognition than language membership.

The effect of non-linguistic context was tested in three single- and mixed-language English-Dutch lexical decision tasks with different instructions (Schulpen, Dijkstra, & Schriefers, 2003). Unsurprisingly, the manipulation of the non-linguistic context led to differences in overall response times for English target words. However, regression analysis with English frequency as the predicting variable did not reveal any interaction between the task and the frequency. Task-related differences in response speed could thus
not be related to the frequency-related word identification system, but to a task/decision system (see Figure 1.8).

**Evaluation of the model.** The Bilingual Interactive Activation model clearly shows that bilinguals cannot resist interference from the non-target language during target language processing and that a certain degree of inhibition is thus required to activate the target language lexical items. Interestingly, interference suppression is one of the components of cognitive control (Bunge et al., 2002). The BIA model can thus be used as a theoretical foundation for understanding why bilinguals show enhanced cognitive control processing.

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**Figure 1.8 The Bilingual Interactive Activation model Plus with a distinction between a word identification system and a task/decision system. Source: Dijkstra & van Heuven (2002, p. 182).**

One of the crucial differences between the monolingual Interactive Activation model (McClelland & Rumelhart, 1981) and the BIA model (Dijkstra & van Heuven, 1998) is the adding of a fourth layer. The question may be raised if this additional layer really makes the processing of lexical
items in bilinguals qualitatively different from that in monolinguals. If the number of lexical items is the relevant distinguishing factor, monolinguals with a large vocabulary size might equally need extensive language control requirements to solve competition between synonyms. A more important distinction might be that bilinguals have two lexical items that correspond to exactly the same concept. However, the monolinguals’ linguistic repertoire is most often also composed of different language variants or of registers that contain dissimilar lexical items for exactly the same concepts.

Therefore, the hypothesis can be put forward that the functional distribution of lexical items plays a more important role than language membership. Bilinguals who use their languages in strictly separate settings, such as one language at home and another one at school, might need less controlled processing to suppress interference from the other language than bilinguals who use both of their languages in the same settings. Interestingly, Costa et al. (2009) proposed that the functional distribution of the languages of a bilingual might determine whether cognitive advantages will be observed or not. This would imply that simultaneous bilinguals who are exposed to both languages at home are more likely to show cognitive advantages than sequential bilinguals who learnt their second language in a classroom setting. If a direct link is assumed between how bilinguals control two language systems and advantages in cognitive control (Hilchey & Klein, 2011), the same variability that is seen in bilingual scores on cognitive control might also be observed on measures of language control. An investigation of the impact of different bilingualism-related factors on lexical access might further test the validity of the BIA model across different populations.

### 3.1.3 Inhibitory Control model

The main research question that the IC model tries to answer is how bilinguals perform a single linguistic task in face of other possibilities. This selection component is assumed to be of vital importance to understand bilingual language functioning. When confronted with linguistic input, the bilingual has more processing options than the monolingual: they may speak one language in the monolingual mode, or mix these two language systems in the bilingual mode (Grosjean, 1997).
The IC model states that the selection of the right output is made possible by the mechanism of inhibitory control over the competing non-target output schemata. Translation of visually presented words is given as an example. It is argued that the selection of the right translation equivalent is similar to the selection mechanisms in domain-general conflict tasks, such as in a Stroop-task during which participants have to inhibit the hue of visually presented colour words in order to read the word. Green (1998, p. 67) argues: “Is this task not also a kind of Stroop task? Bilinguals have to avoid naming the printed word and, instead, produce a translation equivalent and a response.” Green (1998) thus tries to connect control over different language tasks to general-purpose cognitive control.

![Diagram of the Inhibitory Control model](image)

**Figure 1.9 The Inhibitory Control model of lexico-semantic processing.** $G =$ Goal; $I =$ Input; $O =$ Output. Source: Green (1998, p. 69).

**Model description.** The IC model is based on the Norman-Shallice model of executive functioning which tries to explain how our brain regulates cognitive activity in routine and non-routine situations (Norman & Shallice, 1986). Within this framework, behaviour is thought to be specified by *schemata* or series of learned thought and action sequences. When someone sees a written word, many schemata can be activated: it can be written down, its meaning can be retrieved from a mental lexicon, it can be repeated, translated, etc.
The Norman & Shallice model distinguishes between different levels of control over schemata: a lower level called contention scheduling, and a higher level called the supervisory attentional system. Contention scheduling is supposed to be fast and automatic. It ensures that task-relevant schemata are accessed after a certain activation threshold has been reached, at the same time inhibiting other competing schemata. The speed of these processes is linearly related to their frequency of activation. The supervisory attentional system (SAS), in contrast, is supposed to be slow and non-automatic. It is appealed to in novel situations or when automatic schemata are insufficient to solve a certain problem. In addition, it also functions as a monitor in charge of the activation of appropriate schemata and the suppression of inappropriate ones.

Once the SAS has opted for the appropriate task schema, the question arises how the right lexical items are selected. In a first stage, the conceptualiser transmits conceptual information to the lexicosemantic system. Within this system, the operating language task schema can modulate the strength of the representations. The IC model proposes that each lemma contains a certain language tag and that rightful selection is implemented by the suppression of lemmas with incorrect tags. This inhibition is supposed to be reactive, which means that it happens after both target and non-target lemmas that are linked to the concept have been activated (see Figure 1.9).

One important aspect of the IC model is that the amount of inhibition required to suppress non-target lexical items is supposed to be positively related to the extent to which they are activated. The degree of activation, in turn, is related to frequency and proficiency. Hence, more inhibition is needed to suppress lexical items from a high-proficient than from a low-proficient language. An unbalanced bilingual will thus need more inhibition to suppress L1 lexical items during L2 production than to block L2 lexical items during L1 production (see Linck et al., 2012).

An important line of evidence in favour of the IC model has come from studies on the asymmetry of language switching costs, which refers to the observation that switching from L2 to L1 (backward switching) incurs a higher behavioural cost than switching from L1 to L2 (forward switching; e.g. Meuter & Allport, 1999). According to the IC model, processing a second language is suggested to entail strong inhibition of the more
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dominant language (Green, 1998). This inhibition persists during a language switch and leads to negative priming of the L1 lexicon as a whole on a L1 switch trial (Meuter & Allport, 1999).

Evaluation of the model. The IC model is an interesting framework for understanding how controlled processing requirement may influence performance on mixed-language tasks. Hence, it is one of the most widely cited theoretical models that underlie the hypothesis of overlap between language and cognitive control (e.g., Bialystok et al., 2012). Moreover, its predictions regarding the differential involvement of inhibitory control in backward and forward switching can easily be tested (Linck et al., 2012).

Still, a few critical thoughts can be put forward. A first point of criticism relates to the specificity of the processes of inhibition and activation to bilingual language processing. It may be argued that mixed-language tasks, such as translation, are just one example of language tasks that involve selection and inhibition. Green (1998, p. 67) himself refers to this: “On hearing a word a person could retrieve its meaning, write it down, repeat it (again and again), free associate to it, count the number of letters or syllables in it, or translate it into another language.” The degree of automaticity determines how much controlled processing is needed for implementing these tasks (Jeon & Friederici, 2013). In some bilinguals, such mixed-language activities as language switching and translation may be fairly automatized. So, the degree to which bilinguals need more controlled processing might depend on their individual frequency of mixed-language interactions.

Second, there seems to be a mismatch between the explanation given by the IC model for language switching costs and observations in real communicative contexts. The IC model attributes switch costs to the controlled processing required for the suppression of the previous language schema in favour of a new one. This might lead to the idea that bilingual language use is effortful and inefficient compared to single-language use. However, language switching appears to be omnipresent in bilingual communities (Rodriguez-Fornells et al., 2011). It is not supposed to incur a behavioural cost, but it can be fluent and smooth (Grosjean & Miller, 1994). Moreover, it has been shown to be a natural aspect of bilingual discourse in high-proficient and balanced bilinguals (Poplack, 1980; Miccio, Scheffner-Hammer, & Rodriguez, 2009). The IC model fails to
connect the observation that language switching incurs costs due to effortful processing to the fact that code-switching is such an efficient way of communication.

The third point of criticism relates to the generalizability of the IC model to all types of bilingual populations. Asymmetry of language switching, for example, is related to differences in proficiency levels between different languages, and thus tightly linked to unbalanced bilingualism (Meuter & Allport, 1999). In a sample of simultaneous and high-proficient bilinguals, Costa & Santesteban (2004) found symmetrical switching costs. This clearly illustrates the need for investigating what factors contribute to the variability in switching behavior.

3.2 Hemodynamic functional neuroimaging of translation and switching

3.2.1 Translation

Translation paradigms are a logical way to investigate naturalistic mixed-language processing. Translation is a particularly demanding skill that involves different processes such as the analysis and encoding of phonological, morphological and syntactic information into working memory, retrieval of this information in the target language and controlled processing to avoid interference from the source language (Lehtonen et al., 2005). Two directions can be distinguished: forward translation refers to the ability to communicate the meaning of one’s native tongue (as input or source language) in a second language (the target language); backward switching has the second language as source language with the word forms in the native tongue as target.

Two different pathways for translation have been proposed: a non-semantic, direct route in which word forms of translation equivalents are linked at the lemma level, and a semantic, indirect route in which they are connected by their meaning (Jescheniak & Levelt, 1994). According to one psycholinguistic theory of translation, each translation direction is related to a different pathway (Kroll & Stewart, 1994). Forward translation is supposed to rely more on the semantic or indirect route, whereas backward translation would be subserved by a direct or lexical route (Price, Green, & von Studnitz, 1999). In this view, forward translation
would be more represented in neural regions that are devoted to semantic processing, whereas backward translation would be embedded in lexical access regions.

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<td>R</td>
<td>Not reported</td>
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<td></td>
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<td>Putamen/head of caudate</td>
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<td>Cerebellum</td>
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<td>Fusiform g.</td>
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<td>Cerebellum</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1 An overview of hemodynamic functional neuroimaging studies of translation. Highlighted in black are regions that are part of the neural language control network.

An alternative view was proposed by Green (1998) who suggested differential involvement of controlled processing according to the switching direction. On a backward switch or a L1 switch trial, more control would be needed to activate a language that was strongly inhibited
Klein et al. (1994) measured brain activity during back- and forward translation relative to word repetition in each of the languages involved (L1=English; L2=French). A clear differentiation between two different pathways depending on the direction of translation could not be established. Rather, a similar left-lateralized distributed neural network was recruited for the two translation tasks. Different parts of the dorsolateral PFC showed activity for both translation directions, the involvement of which was ascribed to working memory. Price et al. (1999) studied translation mechanisms in German-English bilinguals. The contrast between translation and reading of visually presented words revealed activity in subcortical structures such as the bilateral putamen and the head of the caudate nucleus, and the ACC. Again, no regions turned out to be specifically or differentially implicated in each of the two translation directions.

Unlike previous studies that focused on the translation of isolated words, Lehtonen et al. (2005) used fMRI to investigate the neural correlates of forward sentence translation (from Finnish into Norwegian). Sentence translation turned out to specifically activate the left IFG and the left basal ganglia. The involvement of the anterior part of Broca’s area (BA 47) was related to semantic retrieval (Bookheimer, 2002). Theoretically, this finding was linked to the reliance of forward translation on a semantic route (De Groot, Dannenburg, & van Hell, 1994; see Table 1.1 for an overview of studies).

### 3.2.2 Language mixing and switching

Psycholinguistic studies have uncovered that switching from one language into another is accompanied by a cost in terms of a delay in response times and a decline in accuracy rates (Grainger & Beauvillain, 1987). Even though the existence of this effect is well established, the size of the costs related to the direction of the switch remains a matter of debate. Some studies have reported asymmetric switching costs which refers to higher costs when switching from L2 into L1 than from L1 into L2 (Meuter & Allport, 1999; Wang, Xue, Chen, Xue, & Dong, 2007; Wang, Kuhl, Chen, & Dong, 2009). The
IC model explains this observation by assuming strong inhibition of the more dominant language during L2 processing (Green, 1998). This inhibition persists during a language switch and leads to higher language control requirements in order to activate the L1 lexicon on the switch trial (Meuter & Allport, 1999). On the contrary, other studies found symmetric costs for backward and forward switching (Costa & Santesteban, 2004). This variability could be related to differences in proficiency levels: high-proficient bilinguals are believed to show symmetric switching costs whereas low-proficient bilingualism would lead to asymmetry in language switching.

The neural mechanism required to tear apart two languages in the human brain have been a matter of scientific interest for many decades. Penfield & Roberts (1959) came up with the idea of a language switch at the neurophysiological level in order to account for the lack of interference in bilingual language use. Based on clinical studies, the supramarginal gyrus (SMG) was suggested as the neuroanatomical substrate of language switching (Herschmann & Potzl, 1983; Kauders, 1983). However, other studies reported no switching difficulty for patients with lesions to this specific area in the posterior part of the Sylvian fissure (Gloning & Gloning, 1983; Minkowski, 1983). More recently, a combination of findings from clinical and non-clinical origins has revealed the existence of a language control network in the brain (Abutalebi & Green, 2007). The SMG, part of the inferior parietal lobule, is only one component of this neural circuitry.

Language control in switching contexts can be split up in two different components: sustained and transient language control (Wang et al., 2009). This is in line with a distinction that can be found in the experimental psychological literature on general task switching (Braver et al., 2003). Initially, only sustained control was investigated by contrasting experimental blocks in which two tasks alternated to blocks in which the same task was repeated throughout the entire block (Jersild, 1927; Spector & Biederman, 1976). This mixing cost may be up to 200-300 milliseconds per item (Pashler, 2000). More recently, the focus has shifted to the study of transient control through an analysis of switching costs on a trial-by-trial analysis, by contrasting task-repeat trials to task-switch trials. The neural correlates of these two language control processes can be investigated by using blocked and event-related neuroimaging paradigms, respectively.
**Blocked designs.** The first functional neuroimaging study that engaged a switching paradigm in healthy subjects (Price et al., 1999) reported significant activity for language switching in the bilateral SMG and the IFG. Surprisingly, no activity was detected in other regions that subserve controlled linguistic processing, a finding which might be related to the predictable order in which the language switches were presented. Furthermore, the language switches were collapsed across two different conditions: reading and translation of visually presented words.

These drawbacks were overcome in an fMRI study that comprised single- and mixed-language production in a blocked design (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001). The English-Spanish bilingual participants were presented with single- and mixed-language picture naming blocks. In the mixed blocks, they had to name the picture in the language that corresponded to an accompanying visual cue. Analysis of a small number of regions of interest including most classical language areas revealed that only the dorsolateral PFC was additionally activated during mixed-language versus single-language picture naming. Hernandez et al. (2001) provided evidence that this region is specifically involved in between-language switching. Within-language switching between naming objects (nouns) and actions (verbs) related to the presented pictures did not reveal any increased activity in the dorsolateral PFC.

A later whole-brain analysis of the between-language switching contrast revealed that the PFC activity was only part of a much larger neural network that underlies language switching (Hernandez, 2009). Additional activity was also found in the left superior parietal lobule, the right precentral gyrus and the right supplementary motor area (SMA). All of these regions are involved in automatic language processing related to motor processing, articulation and phonological retrieval, respectively.
Similar results were obtained in a Chinese-English numeral reading task (Wang et al., 2009). The contrast of mixed- and single-language picture naming blocks revealed neural activity in bilateral regions of the PFC. In line with results from interference (Rodriguez-Fornells, Rotte, Heinze, Noesselt, & Muente, 2002) and across-language priming studies (Moss et al., 2005), the involvement of the PFC was related to inhibition of interference from the non-target language. Recruitment of right homologues of this region was linked to sustained attentional control (Braver et al., 2003). Correlation analyses revealed a negative correlation between the magnitude of the mixing cost and the number of activated voxels in the right superior parietal lobule, another region known to subserve shifting and selection of less automatic responses (Connolly, Goodale, Dosouza, Menon, & Vilis, 2000).

To conclude, all studies using blocked designs to investigate language switching (Hernandez et al., 2001; Hernandez, 2009; Wang et al., 2009) show that the PFC is involved in sustained or ongoing language control. This PFC involvement is not restricted to the left hemisphere, but also involves the non-dominant hemisphere (see Table 1.2 for an overview of studies).
**Event-related design.** Are the neural correlates of language switching different in blocked and event-related designs? Wang et al. (2009) compared both types of language switching in Chinese-English bilinguals. Transient language control, as measured by contrasting language-switch to language-repeat trials was reported to activate a left-lateralized frontal-parietal executive circuit including the dorsolateral part of the PFC.

What is the exact function of the dorsolateral PFC in a language control context? Abutalebi et al. (2008) gave a possible answer to this question by investigating L1 naming in bilingual and monolingual modes. First language naming in a bilingual context led to a selective engagement of different language control regions including the left ACC, the caudate nucleus and PFC. Activity in the dorsolateral PFC was not restricted to the bilingual mode, but was also perceived in the task-switching single-language context. In line with these results, the PFC was suggested as a potential candidate for subserving within- and between-language selection processes. Other studies had already shown that this region also appears to underlie selection processes in monolingual language processing (Rodriguez-Fornells et al., 2005), and general executive functioning related to response selection (D’Esposito et al., 1995). In contrast, the left caudate nucleus and ACC would constitute a network specifically involved in between-language selection processes.

Will different neural networks be involved in backward and forward switching? Wang et al. (2007) assessed the neural correlates of general, back- and forward language switching in a bilingual Chinese-English picture naming task. The neuroimaging results showed that general language switching activated the three components of the language control network: the dorsolateral PFC, the right cingulate cortex and the caudate nucleus. The recruitment of these regions was found to depend on the direction of the switch. Forward switching led to additional activity in the ACC. In contrast, backward switching trials did not show any involvement of controlled language processing. Interestingly, more involvement of the neural language control network was not related to higher switching costs. The behavioural data revealed higher switching costs for backward than for forward switching.

The same link between more involvement of controlled processing regions and enhanced performance was found in a study on forward switching in
Japanese-born late learners of English (Hosoda, Hanakawa, Nariai, Ohno, & Honda, 2012). All participants performed an English vocabulary test. A correlation analysis between the scores on this test and neural activity induced by forward switching revealed a specific interaction between L2 fluency and activity in the right PFC. More proficiency in English was linearly related to more activity in that specific region during forward switching. Hence, it was proposed that the right PFC plays a role in the selection of phonological representations from a non-dominant language lexicon in late and unbalanced bilinguals.

Two subsequent studies have attempted to further dissociate the components of the neural language control network in language switching. Garbin et al. (2011) proposed a different involvement of the ACC and the caudate nucleus according to the direction of the switch. Participants to this study were highly proficient Catalan-Spanish bilinguals who were asked to complete a bilingual picture naming task inside the MRI scanner. Based on comparisons between switch and repeat trials in L1 and L2, it was concluded that each of the two components of controlled linguistic processing was linked to different switching directions: backward switching would rely on neural circuitry in the pre-SMA/ACC, whereas forward switching was subserved by the caudate nucleus. The validity of this conclusion was refuted, though, by direct comparisons between the two switch directions. Backward switching, compared to forward switching, not only activated the pre-SMA/ACC but also the right caudate nucleus, exactly the region thought to be specifically involved in forward and not in backward switching. Even more surprisingly, the caudate nucleus was not significantly activated in the contrast between forward and backward switching.

In a more recent study with trilingual participants, a proficiency-based differentiation was reported between the neural modulation of the ACC and the caudate nucleus in language switching (Abutalebi et al., 2013b). Participants were native speakers of German who learnt Italian at an early age, followed by English later in life. Switching from German into Italian or from German into English led to similar activation increases in the ACC. Activity in the caudate nucleus, however, showed a different pattern: switching into a low proficient L3 led to significantly higher signal increases than switching into L2. This corresponds to a major functional distinction between the ACC as being involved in proficiency-independent
language monitoring, and the caudate nucleus, in charge of proficiency-dependent language selection.

<table>
<thead>
<tr>
<th>Study</th>
<th>Method</th>
<th>Contrast</th>
<th>Active brain region</th>
<th>H</th>
<th>BA</th>
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<td>Post. middl. temp. g.</td>
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<td>dI PFC.</td>
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<td>Caudate nucl.</td>
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<td>ACC</td>
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<td>Temp. pole</td>
<td>R</td>
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<td>Precentral g.</td>
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<td>STG</td>
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<td>SMA</td>
<td>Inf. occip.</td>
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<td>Fw. vs. bw. sw.</td>
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<td>Cerebellum</td>
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<td>37</td>
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</table>

Table 1.3 An overview of hemodynamic functional neuroimaging studies of language switching using an event-related design. Highlighted in black are regions that are involved in controlled language processing.
Finally, one study has investigated the neural correlates of being exposed to auditory language switches instead of actively producing them (Abutalebi et al., 2007). Participants were Italian-French bilinguals who reported more exposure to their second language. Conjunction analysis of all switching contrasts revealed increased activity in the bilateral inferior PFC and the middle temporal cortex. The involvement of the neural language control network turned out to be different for backward and forward switching. In contrast to previous studies (see Wang et al., 2007), forward switching activated a neural network encompassing regions typically involved in controlled language processing, such as the left caudate and the bilateral ACC, the posterior cingulate cortices and the SMG. Backward switching only increased activity in superior parietal and temporal areas. The surprising observation that L1 processing would require more controlled processing than L2 processing was related to the nature of the task (a comprehension task) and the low exposure of the participants to their mother tongue.

To conclude, studies on language switching using event-related designs show much more contradictory results than those with blocked designs (see Table 1.3 for an overview of studies). First, much disagreement has arisen about the functional distinction between the PFC and the ACC. Whereas Hernandez et al. (2001) proposed that the PFC underlies inhibition and selection processes specifically involved in mixed-language processing, Abutalebi et al. (2008) attribute this role to the ACC. A second point of controversy is how language control requirements are associated to the direction of the switch. While Abutalebi et al. (2007) showed that backward switching relies more on controlled processing regions than forward switching, Wang et al. (2007) showed exactly the opposite: only forward switching activated the neural language control network.
Chapter 2
Data report

Chapter 1 has shown that bilinguals rely on a neural language control network during many bilingual activities. Controlled processing is not only required in mixed-language processing, such as during translation or language switching, but it is also related to the neural L2 cost or the additional resources that are needed to process a less proficient language. Furthermore, the neural network that subserves language control shows overlap with the regions involved in general-purpose cognitive control.

The following section reports data from two studies that intended to explore the overlap between language and cognitive control: a longitudinal study in different populations of bilingual children and a group of monolingual controls; and a cross-sectional study with two bilingual populations of young adults. Participants to both studies completed a couple of language and cognitive tests. In this chapter, only the language tests are discussed.

At the first time point of the longitudinal study with bilingual children, all participants underwent an extensive language test battery which was composed of single-language tasks, an interference task and a translation task. At the second time point, only single- and mixed-language phonemic verbal fluency tasks were administered. The difference between these two tasks, or the mixing cost, was used as a measure of language control abilities. In the cross-sectional study, all participants performed the same mixed-language phonemic verbal fluency task in addition to an fMRI bilingual semantic categorization task. The inclusion of this task allowed for a comparison between the behavioural and neural correlates of language-switch and language-repeat trials, both in the forward and backward switch directions.
1 Longitudinal study

1.1 T1

Most studies on controlled processing in bilinguals have given little attention to the vast variation between bilingual individuals. Some studies have recruited bilingual groups that were composed of individuals with widely varying language backgrounds (Bialystok et al., 2004; Bialystok, Craik, Grady, Chau, & Ishii, 2005; Carlson & Meltzoff, 2008; Martin-Rhee & Bialystok, 2008). Another problem is the lack of objective measurements to test language proficiency (Bialystok et al., 2005b; Bialystok et al., 2006) or the absence of key background information such as the manner of second language acquisition (e.g., Kousaie & Phillips, 2012). If quantitative measures were included, most often only one language (e.g., L2) or one aspect of language processing (e.g., vocabulary) was tested (e.g., Bialystok et al., 2004; Bialystok et al., 2005b; Morton & Harper, 2007).

Even in the few studies that intended to investigate the variability in bilingual populations, the relevant factors that could have an effect on controlled processing skills were not isolated from each other. Luk, De Sa and Bialystok (2011), for example, found differences in controlled processing in two groups with different ages of second language acquisition. However, both groups also showed large differences in language proficiency with higher scores on a second-language picture vocabulary test for the early than for the late bilinguals.

The present study intends to report language scores from simultaneous and sequential bilingual children and monolingual children that participated in a longitudinal study on the development of controlled processing. An extensive language test battery was used to assess between-group differences in language proficiency for both languages involved.
### Table 1.4 Key characteristics study population longitudinal study T1.

<table>
<thead>
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<th>Monolinguals</th>
<th>Sequential Bilinguals</th>
<th>Simultaneous Bilinguals</th>
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</thead>
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<td>9 years; 5 months</td>
<td>9 years; 5 months</td>
</tr>
<tr>
<td><strong>Gender (M/F)</strong></td>
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<td>8/8</td>
<td>10/13</td>
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<td>Higher education, master level</td>
<td>Higher education, master level</td>
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<tr>
<td><strong>Median educational level mother</strong></td>
<td>Higher education, master level</td>
<td>Higher education, bachelor level</td>
<td>Higher education, bachelor level</td>
</tr>
</tbody>
</table>

#### 1.1.1 Methods

**Participants.** A total of 54 right-handed children (mean age = 9 years, 5 months, \( SD = 11 \) months; 24 males, 30 females) were selected for this study. Handedness was defined using the Edinburgh Handedness Inventory (Oldfield, 1971). Recruitment was done via the distribution of more than 1,000 paper leaflets in Dutch- and French-speaking primary schools in the Brussels Region and its periphery. The online form of this leaflet was also sent to several mailing lists and was published three times in the VUB newsletter which is weekly sent to all university staff and students. Interested parents were invited to fill out an online form to get more information about the study. A questionnaire on the linguistic, socioeconomic and clinical background of the children was then completed by the parents. Only children without serious physical, psychological or neurological impairments were included. Parental educational attainment was used as an indicator of socioeconomic status. All questionnaires were signed by the volunteer and one of his or her parents. Informed consent was given conform to the legal regulations. The study protocol was approved by the Ethical Committee of the University Hospital of Brussels (UZ-B).

Based on their language background and age of second language acquisition, three main groups were distinguished (see Table 1.4). A first group was composed of 15 *monolingual children* (6 males, 9 females, mean age = 9 years; 7 months; \( SD = 3 \) months), 14 of which had Dutch as their
native tongue. The other monolingual participant indicated French as his native tongue. All monolingual volunteers only spoke one language at home and at school, apart from two hours a week of obligatory instruction in the second language since the third grade (age eight). Even though little exposure to French cannot be excluded, this sample was as close as one can get to a ‘monolingual’ sample in a cosmopolitan city as Brussels.

A second group was composed of 16 sequential bilingual children (8 males, 8 females; mean age = 9 years; 5 months; SD = 15 months), of which fifteen spoke only French and one spoke only German at home and who all started learning their second language at school from a mean age of 2 years and 2 months (SD = 1 year; 3 months) onwards. Children in this group did not or only very rarely use Dutch at home. Sequential bilinguals reported their listening and speaking skills as excellent, but reported poor reading and writing skills in their L1. The reason for this is obvious: this group had never received formal instruction in their first language. L2 proficiency was globally rated as ‘very good’.

A third group was composed of 23 simultaneous bilingual children (10 males, 13 females; mean age = 9 years; 5 months; SD = 11 months). The inclusion criterion for this group was the simultaneous acquisition of two languages from birth according to the ‘one parent, one language’ rule. The parents indicated either Dutch (n = 15) or French (n = 8) as the first language of their child. The reported second languages of the children showed a wider variety: French (n = 10), Dutch (n = 6), Spanish (n = 3), English (n = 2), Italian (n = 1) and Swedish (n = 1). Simultaneous bilinguals reported excellent receptive and productive skills in L1. In L2, however, only listening skills were evaluated as being excellent. Speaking and reading skills were rated as ‘very good’ and writing skills as ‘good’.

Wisconsin Card Sorting Task. The Wisconsin Card Sorting Task (WCST) is a simple objective task to measure an individual’s flexibility in thinking (Berg, 1948). A computerized version of the WCST, part of the The Psychology Experiment Building Language (PEBL) test battery, was used in this study to assess intelligence (Mueller, 2012). Children were tested individually. All participants sat down on a comfortable chair in a quiet and dimly-lit room while they executed the task on a Dell Latitude E6500 with a
15.4-inch screen. Instructions were given in the child’s preferred language by a Dutch-French bilingual speaker.

A total of 128 cards were presented to the children, each with a different arrangement of number (4 possibilities: 1 to 4), colour (4 possibilities: red, green, yellow and blue) and shape (4 possibilities: triangle, star, cross and circle). There were 64 different cards, and each card was presented twice. In the beginning of the task, children were presented with four piles of cards that remained visible throughout the entire task. Each pile had a different number, colour and shape. Children were instructed to match stimulus cards to the right pile; however, no rule was given on how they had to match the cards. After each trial, the child was given feedback on whether the match was right or wrong. The rule changed every 10 cards. The PEBL version of the WCST automatically generates a report with the following psychometric scores: number of categories completed, correct responses, total errors, perseverative responses and errors, non-perseverative and unique errors, and trials to complete first category.

The aim of this test was to control for differences in intelligence between the children. Arffa, Lovell, Podell and Goldberg (1998) reported significant multiple regressions between WCST perseverative errors, non-perseverative errors, total errors, and trials to first category and intelligence test scores. An analysis of variance for perseverative errors also indicated that children with very superior IQs (>130) significantly outperformed children with above average and superior IQs (110 to 129).

Language test battery

Modified versions from several subtests of the Bilingual Aphasia Test (BAT, Paradis, Hummel and Libben, 1987) were included in this language test battery. The BAT is one of the only available test batteries with culturally and linguistically equivalent tests in Dutch and French. The stimulus books, score sheets and instructions were downloaded from the McGill website (McGill, 2013). Participants were tested individually. Instructions for each task were given by a Dutch-French bilingual speaker. Bilingual children took a total of 5 tasks in each language. These tasks can be subdivided into single-language tasks (L1 & L2), an interference task (L1 & L2) and a translation task, in both directions. The order of the languages was
counterbalanced across participants. Evidently, the monolingual children only took the three single-language tasks.

**Single-Language Tasks.** The following three tests were included in the test battery: 1. **Verbal Fluency.** Children were instructed to give as many words as possible starting with a certain letter within one minute. For Dutch these letters were /p/, /v/, and /k/ and for French these letters were /b/, /f/, and /l/. The order was counterbalanced. 2. **Receptive vocabulary** (maximum score = 18). Children heard 18 words and were asked to choose the drawing that best depicted the meaning of the word from four images. 3. **Listening comprehension** (maximum score = 5). The children heard a short story, followed by five simple questions about the contents of the story.

**Interference task.** **Grammatical judgements** (maximum score = 8). The children heard 8 sentences and were asked to assess the grammaticality of these sentences (1 point for each correct response). Some of the sentences contained interference errors from the other language.

**Translation task.** The children heard 10 words in each language and were instructed to give the translation equivalent in the other language (maximum score = 10 for each translation direction).

**Behavioural data analysis**

**Group variables.** SPSS 17.0 was used for all statistical analyses. Group analyses were conducted based on the individual scores on all tasks. One grouping (or independent) variable, containing three levels, was added: language group (levels: monolinguals, simultaneous and sequential bilinguals). Within-subject analyses comparing performance on L1 and L2 scores in bilinguals were conducted by adding language as a within-subject variable with 2 levels (L1 and L2). In order to establish the normality distribution of the samples, one-sample Kolmogorov-Smirnov tests were conducted on all dependent variables. Based on the p-values of these analyses, parametric (p-value > 0.05) or non-parametric tests (p-value < 0.05) were carried out.
1.1.2 Results

Demographic variables. A one-way analysis of variance showed no difference in age distributions between the groups, $F(2,51) = 0.27, p > .05$. A chi-squared test revealed that the groups did not differ by gender, $\chi^2(2, N = 54) = .33, p > .05$. Finally, no differences were found with regards to the educational level of the father, $H(2) = 2.46, p > .05$, or the mother, $H(2) = 3.53, p > .05$.

Wisconsin Card Sorting Task. Data from 1 child (a sequential bilingual) was excluded from further analyses because of a logging error. A one-way analysis of variance showed that on none of the factors that are known to correlate with intelligence scores (Arffa et al., 1998), significant differences were found between the groups: perseverative errors, $F(2,50) = .49, p > .05$, non-perseverative errors, $F(2,50) = 3.16, p > .05$, total errors, $F(2,50) = 1.57, p > .05$, and trials to complete the first category, $F(2,50) = .25, p > .05$.

Self-reported linguistic measures. Non-parametric Kruskal-Wallis tests were used to statistically assess between-group differences on all eight self-reported linguistic measures and within-group differences in the two bilingual samples according to the language involved. These tests with all L1 self-ratings as input revealed no differences for speaking, $H(2) = 5.59, p > .05$, and listening, $H(2) = 4.11, p > .05$. Differences in self-reported measures on reading, $H(2) = 16.38, p < .001$, and writing, $H(2) = 19.88, p < .001$, in contrast, reached significance. Post-hoc Mann-Whitney U analyses revealed that these differences were restricted to the contrasts between monolinguals and sequential bilinguals, both for reading, $U = 33, Z = -3.47, p = .01$, and writing, $U = 24, Z = -3.86, p < .001$, and between simultaneous and sequential bilinguals, also both for reading, $U = 61.50, Z = -3.05, p < .01$ and writing, $U = 48.50, Z = -3.35, p = .001$.

Mann-Whitney U analyses with L2 self-ratings as input did not show any significant differences between sequential and simultaneous bilinguals for all levels of linguistic proficiency on which the latter delivered higher ratings than the former: listening, $U = 106.00, Z = -1.18, p > .05$, speaking, $U = 99.50, Z = -1.40, p > .05$, reading, $U = 118.00, Z = -.69, p > .05$. Only for writing did the sequential bilinguals rate their proficiency higher than the
simultaneous bilinguals, a difference which was shown to be marginally significant, \( U = 88.00, Z = -1.78, p = .09 \).

**Language test battery**

*Receptive vocabulary.* Mean scores and standard deviations are reported in Table 1.5. Data from one child were excluded from further analysis. A one-way analysis of variance on L1 test scores did not show any significant intergroup differences, \( F(2,50) = .70, p > .05 \). Data from 14 sequential and 22 simultaneous bilingual children were used for conducting a mixed-model analysis of variance, modeling both the within-subject variable language and the between-subject variable group. A main effect of language was found, \( F(1,34) = 5.20, p < .05 \), with higher scores for L1 than L2, in addition to a marginally significant interaction effect between language and group, \( F(1,34) = 6.91, p = .07 \), and no effect of group, \( F(1,34) = .33, p > .05 \).

*Verbal fluency.* Mean scores and standard deviations are reported in Table 1.5. The data from two children were not properly logged; hence, they were not included in the analysis. A one-way analysis of variance revealed highly significant differences between the groups on L1 verbal fluency, \( F(2,49) = 9.10, p < .001 \). Bonferroni-corrected post-hoc analyses revealed that only the two pairwise comparisons between the sequential bilinguals and the monolinguals (\( p < .001 \)) and between the sequential and the simultaneous bilingual groups (\( p < .05 \)) were significantly different.

In a subsequent analysis, the variable ‘mother tongue’ was added to the analysis. An independent samples t-test revealed highly significant differences in L1 verbal fluency scores depending on the individual’s mother tongue, \( t(48) = 6.23, p < .001 \). Differences between the two languages involved could be related to the frequencies of the phonemes as onset letter in the respective languages. According to the CELEX lexical database (Baayen, Piepenbrock, & Van Rijn, 1993), the three phonemes that were used in the Dutch-only condition had a mean frequency of 6.56 % as onset letter. In the French-only condition, this was slightly lower with a mean frequency of 5.59 %. In order to control for these differences, an analysis of covariance was conducted with the variable onset frequency as a covariate. As could be expected based on the preceding t-test, the
grouping differences did not reach significance after having controlled for the mother tongue, $F(2,46) = 0.15, p > .05$.

Data from 14 sequential and 21 simultaneous bilinguals were used for further analysis of L2 verbal fluency scores. An independent samples t-test revealed that this difference was not significant, $t(33) = 1.17, p > .05$.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>L1</td>
<td>Dutch or French</td>
<td>French or German</td>
</tr>
<tr>
<td>L2</td>
<td>Dutch</td>
<td>Dutch, French, Spanish, Italian or Swedish</td>
</tr>
<tr>
<td><strong>Mean age (in years) and manner of second language acquisition</strong></td>
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<td></td>
</tr>
<tr>
<td>oAoA L2</td>
<td>2 y.; 2 m.</td>
<td>Birth</td>
</tr>
<tr>
<td>MoA L2</td>
<td>School</td>
<td>Parent</td>
</tr>
<tr>
<td><strong>Median values self-reported language proficiency on a 5-point scale</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Listening L1</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Speaking L1</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Reading L1</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Writing L1</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
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</tr>
<tr>
<td>Speaking L2</td>
<td>Very Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>Reading L2</td>
<td>Very Good</td>
<td>Very Good</td>
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<tr>
<td>Writing L2</td>
<td>Very Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Mean scores and standard deviations on language tests</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rec. voc. L1</td>
<td>15.40 (1.45)</td>
<td>15.20 (1.52)</td>
</tr>
<tr>
<td>List. comp. L1</td>
<td>4.50 (.17)</td>
<td>4.46 (.31)</td>
</tr>
<tr>
<td>Verb. fluency L1</td>
<td>7.95 (2.59)</td>
<td>4.51 (1.23)</td>
</tr>
<tr>
<td>Gramm. judg. L1</td>
<td>5.69 (1.49)</td>
<td>5.28 (.89)</td>
</tr>
<tr>
<td>Rec. voc. L2</td>
<td>13.94 (1.77)</td>
<td>14.71 (2.12)</td>
</tr>
<tr>
<td>List. comp. L2</td>
<td>4.36 (.13)</td>
<td>4.26 (.20)</td>
</tr>
<tr>
<td>Verb. fluency L2</td>
<td>6.21 (1.57)</td>
<td>5.56 (1.68)</td>
</tr>
<tr>
<td>Gramm. judg. L2</td>
<td>5.69 (1.03)</td>
<td>5.89 (1.18)</td>
</tr>
<tr>
<td>Fw. transl.</td>
<td>7.40 (1.06)</td>
<td>7.37 (1.38)</td>
</tr>
<tr>
<td>Bw. transl.</td>
<td>7.60 (1.55)</td>
<td>7.67 (1.46)</td>
</tr>
</tbody>
</table>

Table 1.5 Language background and test scores of the three groups of the longitudinal study, T1.
**Listening comprehension.** Mean scores and standard deviations are reported in Table 1.5. Data from 1 monolingual, 3 sequential bilinguals and 1 simultaneous bilingual child could not be used for further analysis. A non-parametric test was conducted to compare the three samples on listening comprehension proficiency. The group differences turned out not to be significant, $H(2) = 3.35, p > .05$. A total of 33 bilinguals, composed of 14 sequential and 19 simultaneous bilinguals, took the L2 listening comprehension test. Again, the between-group differences were not significant, $U(33) = 131.00, Z = -.81, p > .05$.

**Grammatical judgement.** Mean scores and standard deviations are reported in Table 1.5. A total of 31 bilinguals, composed of 13 sequential and 18 simultaneous bilinguals, took the grammatical judgement tasks in both languages. Independent samples t-tests showed equal grammatical performance for the two groups on L1, $t(29) = .89, p > .05$, and on L2, $t(29) = -.48, p > .05$.

**Translation.** Mean scores and standard deviations are reported in Table 1.5. Tests on forward and backward translation were taken by 34 bilinguals: 14 sequential bilingual children and 20 simultaneous bilingual children. A mixed-model analysis of variance with translation direction as within-subjects factor and the two bilingual groups as between-subjects factor showed no significant main or interaction effects.

### 1.1.3 Short discussion

The participants to the longitudinal study were grouped into three different groups based on their language background: monolinguals, simultaneous and sequential bilinguals. The two bilingual groups differed from each other in that the simultaneous bilinguals had acquired both languages from birth onwards, while the sequential bilinguals had started learning the second language at age 2. Onset ages and manners of acquisition were confounded: while the simultaneous bilinguals had acquired both languages at home, the sequential bilinguals had only been exposed to their second language in a school setting (kindergarten or primary school). This was made evident by the self-reported language measures: the simultaneous bilinguals scored higher on L1 reading and writing than the
sequential bilinguals, who, in turn, assessed their L2 writing skills higher than the simultaneous bilinguals.

Importantly, onset age of acquisition and proficiency were not confounded in this study. An extensive language test battery revealed that both bilingual groups scored equally well on all types of tasks, including single-language tasks, interference tasks and mixed-language tasks. In addition, all three groups showed equal L1 proficiency on a range of single-language tasks.

1.2 T2

Language control abilities can be tested by using translation and switching paradigms. At the previous time point of this longitudinal study, both back- and forward translation skills were assessed. The present study will complement this assessment by adding a mixed- or two-language verbal fluency condition to the test battery. The number of words that are said in a mixed-language condition of the verbal fluency can be taken as an indication of someone’s ability to keep two languages simultaneously available. In order to control for individual differences in lexical access, the scores on the mixed- and single-language conditions were contrasted to calculate a language mixing cost.

1.2.1 Methods

Participants. Out of the 54 participants that were recruited at T1, a total of 40 children (mean age = 11 years; 4 months, SD = 11 months; 19 males, 21 females) returned for participation at T2. This sample was composed of 11 monolingual children (4 males, 7 females, mean age = 11 years; 3 months; SD = 11 months), all of which had Dutch as their native tongue; 14 sequential bilingual children (7 males, 7 females; mean age: 11 years; 4 months; SD = 1 year; 1 month), of which 13 spoke only French and another child only German at home and who all started learning Dutch at school from a mean age of 2 years and 2 months onwards (SD = 10 months); 15 simultaneous bilingual children (8 males, 7 females; mean age = 11 years; 5 months; SD = 11 months). The parents of the simultaneous bilingual children indicated either Dutch (n = 10) or French (n = 5) as the first language of their child. The reported second languages of the children
showed a wider variety: French (n = 7), Dutch (n = 4), Spanish (n = 2) and English (n = 2).

Single- and mixed-language verbal fluency. Participants were instructed to name as many words that start with the given phoneme in their first and second language. In the mixed-language condition, participants were asked to perform the same task, but then by alternating between Dutch and French with no translation equivalents allowed. Three phonemes with an equal distribution as onset sound in Dutch and French words were selected from the CELEX database: /l/, /t/ and /m/ (Baayen et al., 1993). The order of the languages and the onset phonemes was counterbalanced across participants. Participants were tested individually. All spoken instructions and pauses were digitally pre-recorded and administered through headphones. They were given by a Dutch-French bilingual speaker.

Behavioural data analysis

Mixed-language (or mixing) cost. For all bilingual participants, a mixed-language cost was calculated by subtracting the number of words uttered during the mixed-language condition from the mean number of words that were uttered in the two single-language conditions.

Two-means cluster analysis was carried out using SPSS 17.0 to partition the mixed-language costs into 2 similar clusters in which each observation belongs to the cluster with the nearest mean.

Group variables, see section 1.1.1.

1.2.2 Results

Demographic variables. A one-way analysis of variance showed no difference in age distributions between the groups, $F(2,37) = .12, p > .05$. A chi-squared test revealed that the groups did not differ by gender, $\chi^2(2, N = 40) = .79, p > .05$. Finally, no differences were found with regards to the educational level of the father, $H(2) = .81, p > .05$, or the mother, $H(2) = 4.88, p > .05$. 
Mean scores and standard deviations are reported in Table 1.6. A one-way analysis of variance was used to compare the three groups on L1 verbal fluency. The differences between the groups did not reach significance, \( F(2,37) = 1.14, p > .05 \). 14 sequential and 13 simultaneous bilingual children did the task in their L2 and in the two-language condition. Independent samples t-tests were used to compare group performance on these two other conditions and on the mixed-language cost. None of these contrasts, however, turned out to be significant, neither for L2, \( t(25) = -.38, p > .05 \), nor for the switching condition, \( t(25) = .61, p > .05 \), or the mixed-language cost, \( t(25) = -1.20, p > .05 \). Remarkably, many children showed negative mixed-language costs. The two-means cluster analysis created 2 groups: low-proficient mixers with a positive two-language cost (\( M = 2.42; SD = 2.07 \)) and high-proficient mixers with a negative two-language cost (\( M = -2.86; SD = 1.75 \)) (see Figure 1.10).

### 1.2.3 Short discussion

At this second time point of the longitudinal study, a new measure of language control was added to the test battery. Language mixing costs were calculated by contrasting performance on mixed- and single-language versions of a phonemic verbal fluency task. Huge individual variability was observed in terms of both negative and positive mixed-language costs. This can be interpreted as evidence for both facilitative and inhibitory effects of language control in a mixed-language condition. This distinction was validated by a two-means cluster analysis which generated two groups that were labeled as high- and low-proficient mixers. Importantly, the age of acquisition could not predict the size and direction of mixed-language costs.
2 Cross-sectional study II

Switching languages in a laboratory context incurs a behavioural cost in terms of longer response latencies and poorer accuracy (Grainger & Beauvillain, 1987). One of the most striking findings that can be found in the literature on language switching is the existence of asymmetric switching costs, which means that switching from a weaker L2 into the dominant L1 takes more time than from L1 to L2 (Meuter & Allport, 1999). In other words, forward switching costs (L1 to L2) are smaller than backward switching costs (L2 to L1). The reason for this would be that the amount of language control required to inhibit a more dominant language during L2 trials still persists into the L1 switch trial (Green, 1998).
Critically, this asymmetry is associated to differences in proficiency levels. Hence, the effect was expected only to be present in unbalanced bilinguals. This was confirmed by Costa & Santesteban (2004), who reported symmetric rather than asymmetric switching costs in a sample of highly proficient and balanced bilinguals.

What are the neural correlates of switching costs? Previous studies have revealed that language switching is embedded in a neural network that includes the PFC (Hernandez et al., 2001; Hernandez et al., 2009; Wang et al., 2007; Wang et al., 2009), the ACC (Abutalebi et al., 2007; Abutalebi et al., 2008; Garbin et al., 2011), and the caudate nucleus (Abutalebi et al., 2007; Crinion et al., 2006; Garbin et al., 2011). This network subserves controlled language processing and is similar to a domain-general neural network of controlled processing (Abutalebi & Green, 2007). It is activated when bilinguals speak a language in which they are less proficient or when the two languages have to remain available at the same time (Abutalebi, 2008).

What are the neural correlates of the asymmetry in language switching that have been reported in unbalanced bilinguals? It may be argued that higher switching costs are accompanied by a higher degree of controlled processing as indicated by the recruitment of more components of the language control network. The reasoning goes as follows: if asymmetry in language switching is caused by lingering inhibition from the previous trial (Green, 1998), this will manifest itself by more neural activity in exactly those regions that subserve language control.

Previous functional neuroimaging studies, however, have shown that the regions of controlled processing that are involved in for- and backward switching may depend on bilinguals’ age of second language acquisition. In an event-related fMRI study of language switching in Chinese-born late learners of English, Wang et al. (2007) reported additional activity in the left PFC and the ACC during forward switch trials. In contrast, backward switching did not show any involvement of the neural language control network. Abutalebi et al. (2007) reported the opposite pattern in an fMRI study on auditory language switching in Italian-French early bilinguals: backward switching activated the ACC and the caudate nucleus, while forward switching did not result in any controlled processing. Finally, Garbin et al. (2011) proposed that both forward and backward switching
were subserved by controlled processing in early bilinguals. Importantly, asymmetry in behavioural language switching costs does not necessarily mean that less language control is needed during forward switching. Wang et al. (2007) reported no involvement of controlled processing in backward switching, but still (behavioural) backward switching costs were much higher than forward switching costs.

One possible reason for these differences might be that the recruitment of the neural language control network may have facilitative or inhibitory effects on performance, depending on the direction of the switch. More recruitment of language control regions during L1 to L2 switches might facilitate L2 processing on the subsequent trial, while the same amount of language control inhibits L1 processing on a switch trial. In fact, most L1 processing is fairly automatized, while L2 processing requires control (Abutalebi, 2008). The lingering inhibition of a previous L2 trial might prevent automatic access to the L1 lexicon, thereby incurring a backward switching cost. In contrast, language control that underlies the forward language switch might speed up L2 processing, because the controlled processing which is required to compensate for its lower proficiency is already available to enable the forward switch.

A second possible reason for these different results is that previous studies did not control for differences in general controlled processing abilities. Linck et al. (2012) showed that performance on a trilingual picture naming switching task could be reliably predicted by individual scores on a Simon task, which is a widely used indicator of cognitive control skills (Simon & Rudell, 1967). This effect has only been attested in unbalanced bilinguals.

The present study

The present study will investigate the behavioural and the neural correlates of second language, backward and forward switching costs in two bilingual groups of simultaneous and sequential bilingual groups. Previous studies have indicated that the onset age of acquisition determines whether switching costs are symmetrical or not (see, Meuter & Allport, 1999; Costa & Santesteban, 2004). More recently, language switching was shown to depend on general cognitive control abilities in a group of late trilinguals (Linck et al., 2012). In order to control for
differences in controlled processing, all participants were also tested on language control abilities in a bilingual verbal fluency task. These scores were used to regroup the participants according to their language control skills. The present study intends to investigate if these two relevant factors (onset age of acquisition and language control abilities) interact. The design used in this study allows us to disentangle the impact of age of acquisition and language control on switching costs. The aim will not be to reveal what neural regions are active in a specific group of bilinguals during cognitive processing, but rather to explain the neurofunctional correlates of behavioural differences. Therefore, only the relevant grouping variable will be taken into account for the neuroimaging analysis.

This study is the first to examine individual variability in the neural correlates of L2 processing and of forward and backward switching costs. While many studies have investigated the variables that are responsible for the degree of control needed to process a second language (e.g., Kim et al., 1997), no studies were found doing the same for switching costs.

2.1 Methods

Participants. A total of 25 Dutch-French right handed bilingual university students from the Dutch-speaking Vrije Universiteit Brussel in Belgium (mean age = 20.55 years; $SD = 1.92$ years; 13 males, 12 females) were selected for this study. Handedness was defined using the Edinburgh Handedness Inventory (Oldfield, 1971). Participants completed a medical anamnesis. Only participants without serious physical, psychological or neurological impairments were included. Based on their onset age of L2 acquisition and self-rated proficiency, participants were divided into two groups: (i) Dutch-dominant simultaneous bilinguals (Sim. Bil.) [onset age of L2 acquisition (oAoA L2) = 0 in L1 and L2 for all 13 participants (7 males, 6 females), mean age = 20.54 years; $SD = 0.50$ yrs.]; (ii) Dutch-dominant sequential bilinguals (Seq. Bil.) [mean oAoA L2 = 9.25; $SD = 0.25$ yrs.; 12 participants (6 males, 6 females), mean age = 20.56 years; $SD = 0.61$ yrs.]. Despite the objective differences in age and manner of acquisition between the two groups, all simultaneous bilinguals but one labeled Dutch as their first and French as their second language (see Table 1.7).
All participants completed a language background questionnaire including questions about their manner of language acquisition, self-rated language proficiency on a 5-point scale, exposure and use in the two languages. Simultaneous bilinguals had acquired both languages at home from birth, each of the two languages being spoken by one or two of their parents. Sequential bilinguals spoke Dutch to both of their parents and started learning French at elementary school. All participants had also learnt English from age 12 in a school context. At the point of examination, Dutch was for all participants the principal language they had been using and still used at school.

Language test battery

*Single- and mixed-language phonemic verbal fluency.* For a detailed description of this task, see 1.2.1 Methods.

*Grammatical judgement task.* For a detailed description of this task, see 1.1.1 Methods. All spoken instructions and pauses were digitally pre-recorded and administered through headphones. They were given by a Dutch-French bilingual speaker.

*Two-language semantic categorization task.* Participants were tested individually. They sat down on a comfortable chair in a quiet and dimly-lit room while they executed the task on a Dell Latitude E6500 with a 15.4-inch screen. The task was programmed in E-Prime 2.0. Participants were instructed to press the left button if they saw an animal word (78 words) and the right button if they saw the name of an object (78 words). Instructions were given in the participant’s preferred language by a bilingual speaker. Language was manipulated by a random alternation between French and Dutch words. The task was composed of 156 trials, divided according to a 2x2 factorial design: 39 Dutch animal words, 39 Dutch object words, 39 French animal words, 39 French object words. Words were selected from the CELEX database (Baayen et al., 1993) and carefully matched for frequency, word length and number of syllables. Imageability was controlled for by excluding high-frequency abstract objects with low imageability.
<table>
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<tr>
<th>Simultaneous Bilinguals</th>
<th>Sequential Bilinguals</th>
</tr>
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<tbody>
<tr>
<td><strong>First and second language</strong></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>Dutch</td>
</tr>
<tr>
<td>L2</td>
<td>French</td>
</tr>
<tr>
<td><strong>Mean age (in years) and manner of second language acquisition</strong></td>
<td></td>
</tr>
<tr>
<td>OAoA L2</td>
<td>0</td>
</tr>
<tr>
<td>MoA L2</td>
<td>Parents</td>
</tr>
<tr>
<td><strong>Median values self-reported language proficiency on a 5-point scale</strong></td>
<td></td>
</tr>
<tr>
<td>Listening L1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Speaking L1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Reading L1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Writing L1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Listening L2</td>
<td>Excellent</td>
</tr>
<tr>
<td>Speaking L2</td>
<td>Very good</td>
</tr>
<tr>
<td>Reading L2</td>
<td>Very good</td>
</tr>
<tr>
<td>Writing L2</td>
<td>Very good</td>
</tr>
<tr>
<td><strong>Median values self-reported frequency of language use</strong></td>
<td></td>
</tr>
<tr>
<td>Listening L1</td>
<td>Daily</td>
</tr>
<tr>
<td>Speaking L1</td>
<td>Daily</td>
</tr>
<tr>
<td>Reading L1</td>
<td>Daily</td>
</tr>
<tr>
<td>Writing L1</td>
<td>Daily</td>
</tr>
<tr>
<td>Listening L2</td>
<td>Many times a week</td>
</tr>
<tr>
<td>Speaking L2</td>
<td>Many times a week</td>
</tr>
<tr>
<td>Reading L2</td>
<td>Many times a week</td>
</tr>
<tr>
<td>Writing L2</td>
<td>Once a week</td>
</tr>
<tr>
<td><strong>Mean accuracy scores and standard deviation on semantic cat. task</strong></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>96.16 (2.73)</td>
</tr>
<tr>
<td>L2</td>
<td>90.49 (5.64)</td>
</tr>
<tr>
<td><strong>Mean accuracy scores and standard deviation on gramm. judgm. task</strong></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>69.71 (6.68)</td>
</tr>
<tr>
<td>L2</td>
<td>62.02 (21.42)</td>
</tr>
<tr>
<td><strong>Mean words per minute and standard deviation on verbal fluency task</strong></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>11.67 (3.53)</td>
</tr>
<tr>
<td>L2</td>
<td>9.83 (3.10)</td>
</tr>
<tr>
<td>2L</td>
<td>8.67 (2.35)</td>
</tr>
</tbody>
</table>

Table 1.7 Language background of the two groups of cross-sectional Study II.
**Behavioural data analysis**

*Two-means cluster analysis* was carried out using SPSS 17.0 to partition the scores on the mixed-language verbal fluency task into 2 similar clusters in which each observation belongs to the cluster with the nearest mean. This created two new groups: high-proficient language mixers ($M = 10.10$, $SD = 0.43$) and low-proficient language mixers ($M = 6.93$, $SD = 0.39$) (see Figure 1.11).

*Language- & switch-related performance [semantic categorization task].* For each individual, response times and accuracy scores on trials of the language control were partitioned according to the language of the trial itself and the preceding trial. This created a 2x2 design with 2 within-subject factors: Language and Switch, and 4 levels: L1 repeat, L1 switch, L2 repeat and L2 switch. Alternative terms for the switch trials are backward switch (L1 switch) and forward switch (L2 switch) trials.

*Group variables.* SPSS 17.0 was used for all statistical analyses. Group analyses were conducted based on the individual scores of all language tasks. Two grouping (or independent) variables, each of them containing two levels, were added to the individual mean accuracy scores and response times: mixing proficiency (levels: low and high) and L2 age of acquisition (levels: simultaneous and sequential). In order to establish the normality distribution of the samples, one-sample Kolmogorov-Smirnov tests were conducted on all dependent variables. Based on the p-values of these analyses, parametric (p-value > 0.05) or non-parametric tests (p-value < 0.05) were carried out.

*MRI parameters.* MRI scans were acquired on a Philips Achieva 3T MR system (software release 2.5) using an 8 channels SENSE head coil. BOLD sensitive T2* weighted fMRI images were acquired using a spin-echo, echo-planar sequence (EPI) comprising 130 dynamics. Other imaging parameters were: TR/TE=3000ms/ 35 ms, FOV=212 x 98.5 x 230 mm$^3$ covering 22 oblique axial 4mm slices with 0.5 mm gap and matrix size of 104 x 105, total scan duration=402s. Each subject underwent a T1 weighted 3D anatomical scan with following properties: TR/TE=12ms/3.75ms, Field Of View = 200 x 200 x 200mm$^3$, 100 axial 2mm slices, 1x1mm$^2$ voxels, total scan duration = 6 minutes and 30 seconds.
Neuroimaging data analysis: spatial preprocessing. The analysis was performed with SPM5 (Wellcome Department of Cognitive Neurology, London, UK) running in MATLAB 7. The scan files were converted from the Philips PAR/REC format to the Nifti format using r2agui v2.6. The functional scans of each individual were motion-corrected by realigning them to the first volume of the time series using a rigid body registration with a least-squares approach. Then the images were latency-corrected to the 11th slice in each image. The high resolution anatomical scan of each subject was then coregistered to the realigned functional images. The anatomical image of each subject was normalized to the template with a non-linear transformation (Friston et al., 1995). The transformation parameters were applied to the corresponding functional coregistered images. The normalized functional images were spatially smoothed with a Gaussian kernel of 8x8x8 mm³ FWHM.

Neuroimaging data analysis: first-level statistical analysis. In the first level analysis, two general linear models were performed for all participants, first, modelling French and Dutch trials, and second, modelling language switch and repeat trials, separately for each language. The experimental design was convolved with the canonical hemodynamic response function (HRF) and its time and dispersion derivatives (Calhoun, Stevens, Pearlson, & Kiehl, 2004; Hopfinger, Büchel, Holmes, & Friston 2000) to model the event-related activity in a second-order Taylor expansion of the response (Friston, Josephs, Rees, & Turner, 1998; Henson, 2004). The realignment parameters were also included as regressors. The data were high-pass filtered with a cut-off of 1/128 Hz to eliminate low-frequency noise. From this first level, t-images of parameter estimates were computed for the following comparisons at each voxel for every participant: French trials minus Dutch trials; Dutch switch trials minus Dutch repeat trials (backward switching contrast); French switch trials minus French repeat trials (forward switching contrast).

Neuroimaging data analysis: second-level statistical analysis. These contrasts were defined for each subject, and the resulting images were used in second level analyses using the mean response times as a covariate. First, one sample t-tests were conducted for each of the groups, separately. Then, an independent samples t-test was carried out to trace group differences. Finally, multiple regression analyses were used to find linear relationships
between response latencies and neural activity across all participants. Results of these analyses were thresholded at a minimum of 10 contiguous voxels, and \( p < 0.001 \), uncorrected for multiple comparisons. Talairach Client (version 2.4.3) was used for automated labelling of the localization of neural activity (Lancaster et al., 1997; Lancaster et al., 2000).

![Figure 1.11](image)

*Figure 1.11* A box plot representing mixing proficiency in two groups of low- and high-proficient mixers as revealed by two-means cluster analysis.

### 2.2 Behavioural results

**Self-rated language proficiency.** Median scores are given in Table 1.7. Eight Mann-Whitney’s U tests were run to evaluate the difference in the responses on the 5-point scale. A significant effect of group was found for L2 listening, \( U = 26.5, Z = -3.02, p < .01 \), L2 speaking, \( U = 9, Z = -3.95, p < .01 \), L2 reading, \( U = 33, Z = -2.63, p < .01 \), and L2 writing, \( U = 30, Z = -2.90, p < .01 \). Eight Mann-Whitney’s U tests showed similar results with regards to L2 frequency of use.
Language test battery

**Verbal fluency.** Mean words per minute and standard deviations are reported in Table 1.7. The number of words for each single-language task and the mixed-language task served as input to conduct mixed-model analyses of variance with group as between-subjects factor and language as within-subjects factor. Results revealed main effects of group, $F(1,22) = 8.17$, $p < .01$, and of language, $F(1,22) = 20.56$, $p < .001$. A t-test with the Dutch and French test scores of the simultaneous bilinguals as paired samples revealed no significant differences between the two languages, $t(11) = 1.43$, $p > .05$. The number of words on the mixed-language task was used for conducting a t-test with the two groups as independent samples. No significant differences were detected, $t(1,22) = 0.97$, $p > .05$.

**Grammatical judgement.** Mean accuracy scores and standard deviations are reported in Table 1.7. Results on the grammatical judgement task revealed main effects of group, $F(1,23) = 21.65$, $p < .001$, and of language, $F(1,23) = 38.57$, $p < .001$, and an interaction effect between group and language, $F(1,23) = 19.11$, $p < .001$. A t-test with the simultaneous bilinguals’ scores on Dutch and French as paired samples revealed no significant differences, $t(11) = 1.19$, $p > .1$, thereby restricting the main effect of language to the lower scores of late bilinguals on the French language test.

**Two-language semantic categorization.** Mean accuracy scores and standard deviations are given in Table 1.7. Results on the semantic categorization task revealed main effects of group, $F(1,22) = 44.15$, $p < .001$, and of language, $F(1,22) = 163.82$, $p < .001$, and an interaction effect between group and language, $F(1,22) = 66.97$, $p < .001$. A t-test with the simultaneous bilinguals’ scores on Dutch and French as paired samples revealed significant differences, $t(11) = 3.34$, $p < .01$, which means that the main effect of language is not restricted to the scores of the sequential bilinguals.

Mean response times and standard deviations are reported in Table 1.8. Mixed-model analyses of variance with 2 within-subject and 2 between-subject factors were carried out. Results revealed a highly significant of language, $F(1,20) = 53.53$, $p < .001$, with faster response times for the L1 (Dutch) than for the L2 (French). This language effect was complemented
by a highly significant interaction with the between-subject factor of age of acquisition, $F(1,20) = 19.93, p < .001$, but not with mixing proficiency, $F(1,20) = .34, p > .05$. No main effect of switch was detected, $F(1,20) = 2.68, p > .05$. However, significant interactions were found between language and switch, $F(1,20) = 6.29, p < .05$. In addition, the effect of switch trials was dependent on the language involved, with positive backward and negative forward switching costs, $F(1,20) = 6.29, p < .05$ (see Figure 1.12).

The interaction between switch and language turned out to be significantly different depending on the grouping variable of mixing proficiency, $F(1,20) = 6.29, p < .05$. Mixed-model analyses of variance for high- and low-proficient bilinguals, separately, revealed a significant interaction effect between Switch and Language for the former group, $F(1,9) = 5.36, p < .05$, but not for the latter, $F(1,13) = .06, p > .05$. This means that a facilitative effect in forward switching was only found in the high-proficient language mixers. Low-proficient language mixers, on the other hand, showed equal switching costs in L1 and L2 (see Figure 1.13). Marginally significant interaction effects were found between language, switch and age of acquisition, $F(1,20) = 3.01, p < .10$, and between all of these factors and mixing proficiency, $F(1,20) = 3.75, p < .10$ (see Table 1.9 for an overview of all significant effects).

**Forward & backward switching cost.** Switching costs in milliseconds for (i) L2 switch trials versus L2 repeat trials (forward switching cost) and (ii) L1 switch trials versus L1 repeat trials (backward switching cost) were calculated for all participants. A two-way analysis of variance was run. A main effect of mixing proficiency was only found on the forward switching cost, $F(1,24) = 12.28, p < .01$, with a higher switching cost for low-proficient mixers ($M = 31.61; SD = 69.71$) than for high-proficient mixers ($M = -39.60; SD = 69.71$).
### Table 1.8 Mean response times for L1 and L2 repeat and switch trials in a two-language semantic categorization task according to onset age of L2 acquisition and mixing proficiency. Standard deviations are given between brackets.

<table>
<thead>
<tr>
<th></th>
<th>L1 Repeat</th>
<th>L1 Switch</th>
<th>L2 Repeat</th>
<th>L2 Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim. Bil.</td>
<td>H-prof. l. mix.</td>
<td>719.55 (83.25)</td>
<td>734.27 (90.95)</td>
<td>809.76 (74.20)</td>
</tr>
<tr>
<td></td>
<td>L-prof. l. mix.</td>
<td>745.01 (129.27)</td>
<td>776.79 (155.34)</td>
<td>761.13 (86.24)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>730.16 (100.14)</td>
<td>751.99 (117.33)</td>
<td>789.50 (79.59)</td>
</tr>
<tr>
<td>Seq. Bil.</td>
<td>H-prof. l. mix.</td>
<td>580.64 (33.77)</td>
<td>644.04 (29.80)</td>
<td>841.60 (61.64)</td>
</tr>
<tr>
<td></td>
<td>L-prof. l. mix.</td>
<td>790.03 (194.67)</td>
<td>813.11 (171.33)</td>
<td>987.51 (156.49)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>737.69 (191.67)</td>
<td>770.84 (165.40)</td>
<td>951.03 (151.18)</td>
</tr>
<tr>
<td>Total</td>
<td>H-prof. l. mix.</td>
<td>677.88 (96.83)</td>
<td>707.21 (87.24)</td>
<td>819.31 (68.93)</td>
</tr>
<tr>
<td></td>
<td>L-prof. l. mix.</td>
<td>773.95 (170.19)</td>
<td>800.14 (160.67)</td>
<td>906.66 (173.29)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>733.92 (149.60)</td>
<td>761.42 (140.57)</td>
<td>870.26 (144.11)</td>
</tr>
</tbody>
</table>

Table 1.9 Overview of highly significant (p-value < .01) and significant (p-value between .01 and .05) effects in a two-language semantic categorization task.

**Highly significant effects**

- Language: 53.53
- Language * Onset age of L2 acquisition: 19.93
- Switch * Switching proficiency: 9.08

**Significant effects**

- Language * Switch: 6.29
- Language * Switch * Switching Proficiency: 7.56
2.3 Neuroimaging results

*Within-group analyses: neural L2 cost.* The French-minus-Dutch contrast images of the two-language semantic categorization task were used for conducting one sample t-tests in the two language groups with individual mean response times on French trials as a covariate. The simultaneous bilinguals showed activity in the left insula (BA 13), the left dorsolateral PFC (BA 9) and two peaks of activation in the left precentral gyrus (BA 6). For sequential bilinguals, the neural L2 cost led to 3 activation peaks of activity in the left dorsolateral PFC (BA 9 & 46), and activity in the bilateral middle occipital gyri (BA 18), the left medial frontal gyrus (BA 8), the right dorsolateral PFC (BA 9), the bilateral insulae (BA 13), the bilateral bodies of the caudate nuclei, the right head of the caudate nucleus and the right ACC (BA 32). For each of these activated regions, Table 1.10 reports stereotactic coordinates, T-values and cluster sizes.
### Table 1.10 Results of one-sample t-tests on L2-minus-L1 contrast images of the two-language semantic categorization task in simultaneous and sequential bilinguals. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

<table>
<thead>
<tr>
<th>Activated Region</th>
<th>BA</th>
<th>Talairach Coordinates</th>
<th>T-Value</th>
<th>Cluster Size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simultaneous Bilinguals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L Insula</td>
<td>13</td>
<td>-26, 24, 6</td>
<td>6.68</td>
<td>43</td>
</tr>
<tr>
<td>L dl PFC</td>
<td>9</td>
<td>-18, 36, 18</td>
<td>5.56</td>
<td>11</td>
</tr>
<tr>
<td>L Precentral gyrus</td>
<td>6</td>
<td>-44, -4, 30</td>
<td>5.40</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-53, 1, 12</td>
<td>4.67</td>
<td>12</td>
</tr>
<tr>
<td><strong>Sequential Bilinguals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R Middle occ. gyrus</td>
<td>18</td>
<td>34, -83, 4</td>
<td>14.03</td>
<td>341</td>
</tr>
<tr>
<td>L Medial front. g.</td>
<td>8</td>
<td>0, 22, 47</td>
<td>11.55</td>
<td>1258</td>
</tr>
<tr>
<td>L Middle occ. gyrus</td>
<td>19</td>
<td>-24, -83, 10</td>
<td>11.08</td>
<td>680</td>
</tr>
<tr>
<td>L dlIPFC</td>
<td>9</td>
<td>-40, 9, 27</td>
<td>9.96</td>
<td>650</td>
</tr>
<tr>
<td>L Insula</td>
<td>13</td>
<td>-32, 20, 3</td>
<td>9.65</td>
<td>489</td>
</tr>
<tr>
<td>R dlPFC</td>
<td>9</td>
<td>48, 5, 26</td>
<td>8.82</td>
<td>123</td>
</tr>
<tr>
<td>L Caudate (body)</td>
<td>--</td>
<td>-14, 1, 17</td>
<td>6.49</td>
<td>177</td>
</tr>
<tr>
<td>L dlIPFC</td>
<td>46</td>
<td>-42, 26, 21</td>
<td>6.42</td>
<td>66</td>
</tr>
<tr>
<td>R Insula</td>
<td>13</td>
<td>36, 22, 4</td>
<td>6.28</td>
<td>294</td>
</tr>
<tr>
<td>R Caudate (body)</td>
<td>--</td>
<td>14, 3, 16</td>
<td>5.76</td>
<td>19</td>
</tr>
<tr>
<td>R Caudate (head)</td>
<td>--</td>
<td>12, 2, 2</td>
<td>5.38</td>
<td>92</td>
</tr>
<tr>
<td>R ACC</td>
<td>32</td>
<td>10, 38, 20</td>
<td>5.20</td>
<td>14</td>
</tr>
<tr>
<td>L dlIPFC</td>
<td>46</td>
<td>-46, 28, 8</td>
<td>4.83</td>
<td>32</td>
</tr>
</tbody>
</table>

*Between-group analyses: neural L2 cost.* The L2 contrast images were used for conducting an independent samples t-test comparing simultaneous and sequential bilinguals with mean response times on French trials as a covariate. Additional activity in simultaneous bilinguals was found in the left precentral gyrus (BA 6), the left parahippocampal gyrus (BA 19), two clusters in the left inferior parietal lobule (BA 39 & 40), two clusters in the left precuneus (BA 7 & BA 31), the left superior parietal lobule (BA 7), the right cuneus (BA 19) and the right middle temporal gyrus (BA 39). Additional activity in sequential bilinguals was found bilaterally in the middle occipital gyri (BA 18 & 19), two clusters in the left insula (BA 13) and one in the right insula (BA 13), and two clusters in the left dorsolateral PFC (BA 9 & 46). For each of these activated regions, Table 1.11 reports stereotactic coordinates, T-values and cluster sizes.
Table 1.11 Results of independent samples t-test on contrast images of French trials of the two-language semantic categorization task in simultaneous and sequential bilinguals. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

Within-group analyses: the backward switch cost. The contrast images subtracting neural activity on L1 repeat trials from neural activity on L1 switch trials (the backward switch contrast) were used for conducting within-group analyses in the low- and highly proficient language mixers with individual mean response times on L1 switch trials as a covariate. The results revealed activity in the left middle temporal gyrus (BA 22) for high-proficient language mixers and in two clusters in the left dorsolateral prefrontal cortex (BA 9) in the low-proficient language mixers. For each of these activated regions, Table 1.12 reports stereotactic coordinates, T-values and cluster sizes.
Table 1.12 Results of one-sample t-tests on backward switch contrast images of the two-language semantic categorization task in low- and high-proficient language mixers. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

<table>
<thead>
<tr>
<th>ACTIVATED REGION</th>
<th>BA</th>
<th>TALAIRACH COORDINATES</th>
<th>T-VALUE</th>
<th>CLUSTER SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH-PROFICIENT LANGUAGE MIXERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L Middl. temp. g.</td>
<td>22</td>
<td>-50, -45, -1</td>
<td>7.13</td>
<td>79</td>
</tr>
<tr>
<td>LOW-PROFICIENT LANGUAGE MIXERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L dl PFC</td>
<td>9</td>
<td>-48, 19, 32</td>
<td>4.87</td>
<td>20</td>
</tr>
<tr>
<td>L dl PFC</td>
<td>9</td>
<td>-38, 19, 38</td>
<td>4.72</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 1.13 Results of independent samples t-tests on backward switch contrast in the two-language semantic categorization task in low- and high-proficient language switchers. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

<table>
<thead>
<tr>
<th>ACTIVATED REGION</th>
<th>BA</th>
<th>TALAIRACH COORDINATES</th>
<th>T-VALUE</th>
<th>CLUSTER SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH &gt; LOW PROFICIENT LANGUAGE SWITCHERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L Precentral gyrus</td>
<td>4</td>
<td>-40, -23, 51</td>
<td>5.10</td>
<td>124</td>
</tr>
<tr>
<td>R Medial frontal gyrus</td>
<td>6</td>
<td>8, -18, 62</td>
<td>4.73</td>
<td>83</td>
</tr>
<tr>
<td>L Middle front gyrus</td>
<td>6</td>
<td>-24, -11, 58</td>
<td>4.50</td>
<td>30</td>
</tr>
<tr>
<td>L Lingual gyrus</td>
<td>19</td>
<td>-18, -47, 2</td>
<td>4.18</td>
<td>12</td>
</tr>
<tr>
<td>L Parahippocamp. g.</td>
<td>30</td>
<td>-16, -37, -3</td>
<td>4.16</td>
<td>18</td>
</tr>
<tr>
<td>LOW &gt; HIGH PROFICIENT LANGUAGE SWITCHERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R ACC</td>
<td>24</td>
<td>6, -6, 24</td>
<td>4.54</td>
<td>12</td>
</tr>
</tbody>
</table>

Between-group analyses: backward switch cost. The backward switch contrast images were used for conducting an independent samples t-test between low- and high-proficient language mixers with individual mean response times as a covariate. Additional activity for high-proficient language mixers was found in the left precentral gyrus (BA 4), the right medial frontal gyrus (BA 6) and the left middle frontal gyrus (BA 6), the left lingual gyrus (BA 19) and the left parahippocampal gyrus (BA 30). Relative to the high-proficient language switchers, the low-proficient language switchers activated the right ACC (BA 24). For each of these activated regions, Table 1.13 reports stereotactic coordinates, T-values and cluster sizes.
### Table 1.14 Results of regression analysis on backward switch contrast images of the two-language semantic categorization task with individual mean response times on L1 switch trials added as a regressor. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

**Regression analysis: backward switch cost.** The backward switch images of all participants were used to perform a regression analysis with the individual mean response times added as a regressor. Slower responding was associated with BOLD signal increases in a neural network that was composed of the right middle frontal cortex (BA 6), two clusters in the right ACC (BA 24 & BA 33), three peaks of activity in the right posterior cingulate cortex (BA 31), bilaterally, in the precentral gyrus (BA 4), in the body of the caudate nucleus, and in the middle occipital gyrus (BA 19), the left dorsolateral PFC (BA 9), the left precuneus (BA 7), the left superior temporal gyrus (BA 38), the right paracentral lobule (BA 7), the right medial frontal gyrus (BA 8) and the left thalamus. For each of these activated regions, Table 1.14 reports stereotactic coordinates, T-values and cluster sizes.

<table>
<thead>
<tr>
<th>ACTIVATED REGION</th>
<th>BA</th>
<th>TALAIRACH COORDINATES</th>
<th>T-VALUE</th>
<th>CLUSTER SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>R Middle frontal</td>
<td>6</td>
<td>34, -7, 45</td>
<td>5.81</td>
<td>85</td>
</tr>
<tr>
<td>R ACC</td>
<td>24</td>
<td>12, 4, 38</td>
<td>5.78</td>
<td>489</td>
</tr>
<tr>
<td>R Post. Cingulate</td>
<td>31</td>
<td>30, -63, 20</td>
<td>5.27</td>
<td>101</td>
</tr>
<tr>
<td>L Precenr. gyrus</td>
<td>4</td>
<td>-24, -30, 51</td>
<td>5.16</td>
<td>131</td>
</tr>
<tr>
<td>R Precentr. gyrus</td>
<td>4</td>
<td>22, -30, 51</td>
<td>5.03</td>
<td>59</td>
</tr>
<tr>
<td>R Post. cingulate</td>
<td>31</td>
<td>20, -23, 38</td>
<td>4.84</td>
<td>43</td>
</tr>
<tr>
<td>R Caudate (body)</td>
<td>--</td>
<td>18, 13, 21</td>
<td>4.70</td>
<td>52</td>
</tr>
<tr>
<td>L Middl. front. g</td>
<td>9</td>
<td>-50, 17, 36</td>
<td>4.68</td>
<td>30</td>
</tr>
<tr>
<td>R Middle occ. gyrus</td>
<td>19</td>
<td>34, -77, 6</td>
<td>4.63</td>
<td>40</td>
</tr>
<tr>
<td>L Precuneus</td>
<td>7</td>
<td>-14, -46, 48</td>
<td>4.36</td>
<td>16</td>
</tr>
<tr>
<td>R Post. cingulate</td>
<td>31</td>
<td>16, -35, 39</td>
<td>4.31</td>
<td>27</td>
</tr>
<tr>
<td>L Caudate (body)</td>
<td>--</td>
<td>-12, 5, 24</td>
<td>4.30</td>
<td>16</td>
</tr>
<tr>
<td>L Sup. temp. gyrus</td>
<td>38</td>
<td>-34, 6, -31</td>
<td>4.21</td>
<td>20</td>
</tr>
<tr>
<td>R Paracentral lob.</td>
<td>7</td>
<td>18, -42, 48</td>
<td>4.19</td>
<td>37</td>
</tr>
<tr>
<td>R Medial front. g.</td>
<td>8</td>
<td>10, 31, 41</td>
<td>4.06</td>
<td>31</td>
</tr>
<tr>
<td>L Thalamus</td>
<td>--</td>
<td>-20, -19, -1</td>
<td>3.98</td>
<td>13</td>
</tr>
<tr>
<td>R ACC</td>
<td>33</td>
<td>6, 13, 20</td>
<td>3.95</td>
<td>27</td>
</tr>
<tr>
<td>L Middle occ. g.</td>
<td>19</td>
<td>-30, -87, 13</td>
<td>3.81</td>
<td>12</td>
</tr>
</tbody>
</table>
Within-group analyses: forward switch cost. The contrast images subtracting neural activity on L2 repeat trials from neural activity on L2 switch trials (the forward switch contrast) were used for conducting within-group analyses in the high and low proficient language mixers with individual mean response times on L2 switch trials as a covariate. The high-proficient language mixers showed activity in the bilateral thalami, the left superior frontal gyrus (BA 6), the right SMG (BA 40) and the right hypothalamus. The low-proficient language switchers activated the right posterior cingulate gyrus (BA 31), the left IFG (BA 47) and the left thalamus. For each of these activated regions, Table 1.15 reports stereotactic coordinates, T-values and cluster sizes.

<table>
<thead>
<tr>
<th>ACTIVATED REGION</th>
<th>BA</th>
<th>TALAIRACH COORDINATES</th>
<th>T-VALUE</th>
<th>CLUSTER SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH PROFICIENT LANGUAGE MIXERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L Thalamus</td>
<td>--</td>
<td>-12, -20, 18</td>
<td>9.25</td>
<td>44</td>
</tr>
<tr>
<td>L Superior frontal g.</td>
<td>6</td>
<td>-18, 26, 52</td>
<td>8.62</td>
<td>89</td>
</tr>
<tr>
<td>R SMG</td>
<td>40</td>
<td>50, -43, 33</td>
<td>7.92</td>
<td>56</td>
</tr>
<tr>
<td>R Thalamus</td>
<td>--</td>
<td>10, -7, 13</td>
<td>5.89</td>
<td>16</td>
</tr>
<tr>
<td>R Hypothalamus</td>
<td>--</td>
<td>8, -4, -1</td>
<td>5.77</td>
<td>12</td>
</tr>
<tr>
<td>LOW PROFICIENT LANGUAGE MIXERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R Cingulate gyrus</td>
<td>31</td>
<td>10, -33, 37</td>
<td>6.05</td>
<td>19</td>
</tr>
<tr>
<td>L IFG</td>
<td>47</td>
<td>-26, 31, -8</td>
<td>5.46</td>
<td>23</td>
</tr>
<tr>
<td>L Thalamus</td>
<td>--</td>
<td>-2, -28, 16</td>
<td>4.40</td>
<td>12</td>
</tr>
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</table>

Table 1.15 Results on one-sample t-tests on forward switch contrast in the two-language semantic categorization task in low- and high-proficient language mixers. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

Forward switch cost: between-group analyses. The forward switch contrast images were used for conducting an independent samples t-test between high and low proficient language switchers with individual mean response times as a covariate. Additional activity for high-proficient language mixers was found in the left superior frontal gyrus (BA 8), the left precentral gyrus (BA 4), the left precuneus (BA 19), the bilateral ACC (BA 24, 25 & 32) and the left dorsolateral PFC (BA 9). The low-proficient language switchers did not show any suprathreshold activity. For each of these activated regions, Table 1.16 reports stereotactic coordinates, T-values and cluster sizes.
### Table 1.16
Results of independent samples t-test on forward switch contrast images of the two-language semantic categorization task in low- and high-proficient language mixers. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

<table>
<thead>
<tr>
<th>ACTIVATED REGION</th>
<th>BA</th>
<th>TALAIRACH COORDINATES</th>
<th>T-VALUE</th>
<th>CLUSTER SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH &gt; LOW PROFICIENT LANGUAGE MIXERS</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>L Sup. frontal gyrus</td>
<td>8</td>
<td>-40, 16, 45</td>
<td>4.93</td>
<td>119</td>
</tr>
<tr>
<td>L Precentral gyrus</td>
<td>4</td>
<td>-50, -13, 49</td>
<td>4.41</td>
<td>28</td>
</tr>
<tr>
<td>L Precuneus</td>
<td>19</td>
<td>-14, -82, 39</td>
<td>4.33</td>
<td>24</td>
</tr>
<tr>
<td>R Cingulate gyrus</td>
<td>24</td>
<td>16, -7, 46</td>
<td>4.32</td>
<td>11</td>
</tr>
<tr>
<td>R ACC</td>
<td>25</td>
<td>4, 0, -3</td>
<td>4.10</td>
<td>11</td>
</tr>
<tr>
<td>L Cingulate gyrus</td>
<td>32</td>
<td>-4, 25, 36</td>
<td>4.06</td>
<td>32</td>
</tr>
<tr>
<td>L dl PFC</td>
<td>9</td>
<td>-20, 46, 35</td>
<td>3.97</td>
<td>10</td>
</tr>
<tr>
<td>LOW &gt; HIGH PROFICIENT LANGUAGE MIXERS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No suprathreshold activity</td>
<td></td>
<td></td>
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</table>

### Table 1.17
Results of regression analysis on forward switch contrast images of the two-language semantic categorization task with individual mean response times on L2 switch trials added as regressor. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

<table>
<thead>
<tr>
<th>ACTIVATED REGION</th>
<th>BA</th>
<th>TALAIRACH COORDINATES</th>
<th>T-VALUE</th>
<th>CLUSTER SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Sup. par. lob.</td>
<td>7</td>
<td>-38, -54, 56</td>
<td>5.45</td>
<td>70</td>
</tr>
<tr>
<td>L Sup. temp. g.</td>
<td>22</td>
<td>-59, -54, 12</td>
<td>5.36</td>
<td>72</td>
</tr>
<tr>
<td>L Insula</td>
<td>13</td>
<td>-46, -2, 4</td>
<td>5.17</td>
<td>204</td>
</tr>
<tr>
<td>L SMA</td>
<td>6</td>
<td>-12, -5, 59</td>
<td>4.94</td>
<td>108</td>
</tr>
<tr>
<td>R Sup. temp. g.</td>
<td>22</td>
<td>63, -36, 13</td>
<td>4.91</td>
<td>218</td>
</tr>
<tr>
<td>L Middl. front. g.</td>
<td>6</td>
<td>-36, -3, 55</td>
<td>4.89</td>
<td>42</td>
</tr>
<tr>
<td>L Insula</td>
<td>13</td>
<td>-30, 1, 15</td>
<td>4.77</td>
<td>39</td>
</tr>
<tr>
<td>L Sup. temp. g.</td>
<td>22</td>
<td>-63, -40, 11</td>
<td>4.77</td>
<td>28</td>
</tr>
<tr>
<td>L Thalamus</td>
<td></td>
<td>-18, -29, -4</td>
<td>4.61</td>
<td>10</td>
</tr>
<tr>
<td>L ACC</td>
<td>24</td>
<td>-4, 15, 20</td>
<td>4.42</td>
<td>11</td>
</tr>
<tr>
<td>L Inf. par. l.</td>
<td>40</td>
<td>-30, -41, 43</td>
<td>4.40</td>
<td>32</td>
</tr>
<tr>
<td>L Sup. temp. g.</td>
<td>38</td>
<td>-44, 3, -9</td>
<td>4.37</td>
<td>13</td>
</tr>
<tr>
<td>L Postcentral</td>
<td>2</td>
<td>-48, -23, 49</td>
<td>4.13</td>
<td>19</td>
</tr>
<tr>
<td>R Sup. par. lob.</td>
<td>7</td>
<td>30, -50, 58</td>
<td>3.94</td>
<td>25</td>
</tr>
<tr>
<td>R Sup. par. lob.</td>
<td>7</td>
<td>26, -63, 55</td>
<td>3.77</td>
<td>15</td>
</tr>
</tbody>
</table>
Regression analysis: forward switch cost. The forward switch images of all participants were used to perform a regression analysis with the individual mean response times on L2 switch trials added as a regressor. Slower responding was associated with BOLD signal increases in a neural network that was composed of the bilateral superior parietal lobules (BA 7), the bilateral superior temporal gyri (BA 22), the left insula (BA 13), the left supplementary motor area (BA 6), the left middle frontal gyrus (BA 6), the left thalamus, the left anterior cingulate gyrus (BA 24), the left inferior parietal lobule (BA 40) and the left postcentral gyrus (BA 2). For each of these activated regions, Table 1.17 reports stereotactic coordinates, T-values and cluster sizes.

2.4 Discussion

The present study investigated the behavioural and neural correlates of language switching in a two-language semantic categorization task. Effects related to the age of acquisition were manipulated by recruiting two groups of simultaneous and sequential bilingual young adults. In addition, scores on a two-language verbal fluency were used to regroup all participants based on their language control abilities. This study intended to examine which of these two factors contributes to the variance in L2 and switching performance, both at the behavioural and at the neural level. With regards to the neuroimaging data, special attention was given to the degree of recruitment of the neural language control network.

Behavioural results: the L2 cost

Response latencies on the two-language semantic categorization task were significantly longer for L2 than for L1 trials, which is indicative of a behavioural L2 cost. The size of this speed cost could be predicted by the age of acquisition of the participants. Indeed, the sequential bilinguals showed higher response times on L2 trials than the simultaneous bilinguals. Interestingly, their switching proficiency as revealed by a two-language verbal fluency task, had no effect on the L2 cost. This implies that the speed of L2 semantic categorization cannot be explained by differences in bilinguals’ language control abilities, but only by differences in length of exposure to the second language.
Behavioural results: switching costs

Importantly, the language of the previous trial had no overall impact on the speed of categorization in the subsequent trial, i.e., language repeat and language switch trials were processed equally fast. Yet, a significant interaction effect was found between the performance on switch trials and the language of the trial. Indeed, whereas a language switch led to slower responses on L1 trials, it facilitated L2 processing (see Figure 1.12). This is indicative of asymmetry in language switching (Meuter & Allport, 1999).

Which factor could reliably predict asymmetry in language switching? Both overall and language-related performance on switch trials was significantly different according to the mixing proficiency of the participants. This means that high-proficient language mixers had slowest overall switching costs, and that this effect was different according to the direction of the switch. Indeed, the low-proficient language mixers showed symmetrical switching costs, whereas the high-proficient language mixers showed asymmetry in language switching (see Figure 1.13).

The critical point here is that only mixing proficiency and not age of acquisition could explain differences in the size and direction of language switching costs. These results are different from Costa & Santesteban (2004), who showed that the mechanisms for language switching were different for L2 learners and highly proficient simultaneous bilinguals. Our study demonstrates that language control abilities might have been a confounding variable in that study. This idea is in line with a recent study that showed a direct relationship between scores on a cognitive control task and language switching proficiency in late trilinguals (Linck et al., 2012).

The results of the present study are not in line with the predictions made by the Inhibitory Control model (Green, 1998). This model assumes that asymmetry in language switching costs can be explained by differences in controlled processing requirements. Backward switching would incur a higher behavioural cost because additional language control is needed to overcome the inhibition of the dominant language on the previous L2 trial. If that was the case, the effect of language control abilities would be more pronounced in backward than in forward switching. However, the present
study shows that only forward switching is positively affected by language control abilities.

**Neural correlates of L2 costs**

The neuroimaging data showed a huge difference in activated areas for simultaneous and sequential bilinguals on the neural L2 cost. Simultaneous bilinguals only activated three left-hemispheric regions, amongst which one small cluster of extra neural activity in the dorsolateral PFC, one of the components of the neural language control network (Abutalebi & Green, 2007). In contrast, sequential bilinguals activated a total of 13 regions, including all three components of the language control network: the bilateral PFC, the bilateral caudate nuclei and the right ACC. These differences are indicative of a neural L2 cost and they may explain the highly significant behavioural interaction effect between language and age of acquisition.

Direct comparisons between the groups confirmed this pattern of activity: additional activity for simultaneous bilinguals was found in frontal, parietal, temporal and occipital regions that subserve task-related or automatic language processing. In contrast, the sequential bilinguals showed additional activity in the left dorsolateral PFC, a region that underlies controlled language processing.

**Neural correlates of switching costs**

Regression analyses showed a different involvement of the neural language control network according to the switch direction. Slower responding on L1 switch or backward switch trials was associated with a large network of active brain regions including all components of the language control network, such as the left dorsolateral PFC, the bilateral caudate nuclei and the right ACC. On the contrary, slower responding on L2 switch or forward switch trials was only associated with controlled activity in the left ACC. It can be concluded, thus, that backward switching relies more on the neural language control network than forward switching. This additional reliance was reflected in the behavioural scores by a significant interaction effect between language and switch. This conclusion was further corroborated by the within-group analyses in high- and low-proficient language mixers,
separately. Whereas both groups did not show any language control activity on forward switching, specifically the low-proficient language mixers showed additional activity in the left dorsolateral PFC during backward switching (see Figure 1.14).

*Figure 1.13 Line chart representing mean response times on two-language semantic categorization task for low-proficient (top) and high-proficient language mixers (bottom) according to language (x-axis) and switching (y-axis).*
Figure 1.14 Axial, coronal and sagittal slices representing the neural backward switch contrast in low-proficient language mixers in the left dl PFC (BA 9).

Figure 1.15 Axial, sagittal and coronal slices indicating a higher neural forward switch contrast in high-proficient language mixers in the left ACC (BA 32).
The involvement of the language control network was different for both groups and depended on the switch direction. On backward switching, low-proficient language mixers showed more activity in the right ACC. Importantly, this difference had no impact on performance because low- and high-proficient language mixers did not show any difference on the speed of backward language switching. In contrast, the size of the forward switch cost could significantly be predicted by the factor of mixing proficiency with higher costs for low- than for high-proficient language mixers. Direct group comparisons on forward switching showed more rather than less neural activity for the group that performed best (see Figure 1.15). Importantly, this network included the bilateral ACC and the left dorsolateral PFC.

Our results show a crucial distinction between forward and backward switching in the use of language control regions. Whereas more involvement of the control network on backward switching can only be observed in low-proficient mixers, the recruitment of the same network leads to improved behavioural performance on forward switching. Individuals with better language control abilities do not necessarily recruit less controlled processing regions, but they use these regions more efficiently in terms of improved proficiency.

These results validate the idea that the recruitment of the controlled language processing network may have facilitative or inhibitory effects on performance, depending on the direction of the switch. More recruitment of language control regions during L1 to L2 switches might facilitate L2 processing on the subsequent trial, while the same amount of language control might inhibit L1 processing on a switch trial. Importantly, the difference in proficiency levels between the two languages has not to be extensive to perceive the facilitative effect because it was observed in simultaneous and sequential bilinguals. To conclude, bilinguals with high language control abilities, no matter their age of second language acquisition, can use controlled processing in such a way that behavioural facilitation is accomplished.
Chapter 3
General conclusion

This part investigated the neural and behavioural correlates of three types of bilingualism-related performance costs: the L2 cost, forward and backward switching costs and the mixing cost. Instead of drawing general conclusions about the impact of bilingualism on these measures, the studies reported in this part focused on the individual variability in these effects.

The first main conclusion of this part was that asymmetry in language switching could not be explained by length of exposure to a second language but by differences in language control abilities. This was discovered by using a 2x2 factorial design in which these two factors could be disentangled (compare to Costa & Santesteban, 2004). This finding highlights that language control abilities should be controlled for in any study that investigates the link between bilingualism and cognition.

The second main conclusion was that not all mixed language tasks lead to behavioural costs in all bilinguals. Most notably mixing costs and forward switching costs showed huge individual variability: some individuals showed negative and others showed positive costs. A negative mixing cost refers to better performance on a mixed- than on a single-language condition. This indicates that language mixing might facilitate linguistic processing in some bilingual individuals. The same could be said about forward switching costs in a two-language semantic categorization task: some individuals showed lower response times on L2 switch than on L2 repeat trials, while others showed the opposite pattern. Whereas this asymmetry in language switching has previously been attributed to a higher need for controlled processing in backward switching (Green, 1998; Meuter & Allport, 1999), this study showed that forward rather than backward switching costs could be explained by differences in language control abilities.

Moreover, mixing proficiency turned out to induce functional plasticity in the regions recruited for forward switching. High-proficient language
mixers showed more rather than less neural activity in the language control network on forward switching. This unexpected combination of more controlled processing and better performance might explain why code-switching is such an efficient way of communication despite the observation in laboratory settings that switching incurs behavioural costs due to effortful processing. Possibly, bilinguals with good language control abilities have learnt how to use controlled processing in such an efficient way that facilitation is accomplished. The link between language control abilities and the sociolinguistic environment will be further discussed in Part Four.

The third conclusion of this part relates to the main question of this dissertation, i.e., *how language control is connected to cognitive control*. Because of the high degree of overlap in the processes that underlie language-specific and domain-general control, measures of language control can be expected to correlate with scores on cognitive control tasks. But will this be true for all three discussed bilingualism-related behavioural costs? No, because each of these costs is differently affected by language control skills. Behavioural facilitation for high-proficient language controllers was detected on forward switch costs, but not on backward switch and L2 costs. Therefore, the following prediction can be made: only on those language control tasks in which the amount of controlled processing is connected to behavioural facilitation, correlations can be expected with scores on cognitive control.
Part Two
Neural and behavioural correlates of cognitive control in bilinguals
One of the most remarkable features of the human species is its ability to swiftly adapt its behavior to a changing environment. Flexibility is needed when automatic behaviour has to be turned off, when a laid down plan has to be modified or when an effortful action should be preferred over a more readily available one (Norman & Shallice, 1986). The behavioural correlates of this capacity for flexibility find their roots in a collection of controlled cognitive processes that are grouped together under the labels of executive functioning (Miyake et al., 2000) or selective attention (Posner & Petersen, 1990).

The first attempts to localize the neural circuitry specialized in control over other cognitive processes came from neuropsychological accounts of the ‘frontal lobe syndrome’ (Feuchtwanger, 1923). The behavioural correlates of this pathology were, among others, related to a dysfunction of the regulation and integration of other behaviours. Luria (1973) was the first to explicitly attribute an executive role to the PFC. Within his Neuropsychological Theory, the PFC was conceived as the structure being involved in the most complex forms of programming, regulating, and verifying other cognitive activities.

Progressively, it became apparent that executive dysfunctions were not exclusively caused by prefrontal lesions. Even though the crucial role of the PFC in executive functioning is still generally accepted, neuroimaging studies with healthy participants have revealed a complex interacting neural network that is composed of anterior and posterior cortical, and subcortical regions (Roberts, Robbins, & Weiskrantz, 2002). Analogous to language processing, executive functioning is embedded in dynamic and flexible neural circuitry.

One key question in the literature on cognitive control theory is whether the processes underlying this skill are unitary or separable into different components. Initially, executive functioning was integrated into models of working memory as a single entity. Baddeley's influential model of short-term memory, for instance, is composed of a central executive system and two slave systems: the phonological loop and the visuospatial sketchpad (Baddeley & Hitch, 1974). The central executive system was proposed to have the following functions: the facilitation of dual-task performance, selective attention, inhibition and the coordination of the slave systems. Baddeley (1986) considered Norman & Shallice's supervisory attentional
system (SAS, 1986) to be a valid candidate of how this executive system functions. Within this framework, the SAS, in charge of willful or deliberate control of behaviour, is complemented by contention scheduling, a term used to refer to a more automatic control system.

A more recent model starts from the assumption that executive functioning as a single entity is part of an attention network made up of three components (Posner & Petersen, 1990). In addition to executive functioning, or resolving conflict among competing responses, these components carry out the functions of alerting, or achieving and maintaining an alert state, and orienting, or the selection of information from sensory input (Fan, McCandlis, Sommer, Raz, & Posner, 2002). Alerting and orienting engage the ‘posterior attentional network’, mainly embedded in right hemispheric frontoparietal circuitry, and the superior temporal lobe near the temporo-parietal junction. These components are separate from the ‘anterior attentional network’ which involves the ACC and the lateral PFC.

The unitary nature of a central executive can be challenged by the observation that scores on traditional executive functioning tests show weak correlations (Miyake et al., 2000). In a study on executive functioning in bilinguals, Paap and Greenberg (2013) found that indicators of a specific executive process in one task (inhibitory control in task A) do not predict indicators of the same process in another task (inhibitory control in task B). However, this does not necessarily discard the unity of executive functioning because of the impurity problem (Burgess, 1997). Executive functioning regulates all other cognitive processes, which makes it difficult to isolate its behavioural correlates. The low internal reliability of measures of controlled processing can also be attributed to the plastic capacities of our brain. Once a task has been practiced, automatic rather than controlled processing becomes in charge of its execution, which will dramatically change the behavioural correlates of these tasks (e.g., Dahlin, Stigsdotter-Neely, Larsson, Bäckman, & Nyberg, 2008). Moreover, there is no general agreement on what executive functioning component a certain test actually measures. The Wisconsin Card Sorting Task is used to measure both ‘inhibition of automatic responses’ and ‘set shifting’ (Miyake et al., 2000).

Many recent models of executive functioning have tried to split it up into various components. Based on a large-scale assessment of controlled
processing in healthy participants, Miyake et al. (2000) distinguished three components of executive functioning: shifting between tasks or mental sets, inhibition of prepotent responses, and updating or monitoring of working memory representations. Dimension reduction analysis validated the three-factor model, yet the three components were still moderately correlated. A certain degree of overlap between different tasks that tap into executive functioning may thus be expected.

The first component, shifting, is sometimes also referred to as ‘task switching’ or ‘mixed-task processing’. It incurs a measurable time cost, particularly when the shifting must be driven internally, rather than by external cues (Spector & Biederman, 1976). This component can be tested by mixed-task designs in which different operations have to be carried out on the same type of stimuli such as when a participant is instructed to switch between adding up and subtracting numbers within the same task. Unlike during shifting visual attention, executive-oriented shifting is embedded in neural circuitry composed of PFC and ACC (Posner & Raichle, 1994).

Updating, being the second component of the proposed model, is supposedly embedded in the dorsolateral portion of the PFC and its function is closely linked to working memory. The term ‘updating’ indicates that the suggested model expands the traditional operationalization of working memory as the passive maintenance of task-relevant information to a system that actively and dynamically manipulates its contents.

Finally, the third component ‘inhibition of prepotent responses’ refers to the ability to consciously suppress interference from an unwanted response. One of the best known examples to measure this is the Stroop task. The traditional version of this task entails the naming of the colour of words that may or may not denote the same colour. If the colour is different from the word meaning, inhibition is required to override the automatic response of reading the word. Interestingly, also the Stroop task appears to activate a neural network that is composed of the ACC and the dorsolateral PFC (Carter & van Veen, 2007). At a neural level, each of the three components can thus not easily be distinguished.
While the three-fold structure of Miyake et al. (2000) has proven to be a fruitful way to understand the complex interactions between different components of cognitive control, other classifications have been put forward since. Bunge et al. (2002) introduced a distinction between interference suppression and response inhibition, which corresponds to a differentiation between two distinct levels of task execution: (target) stimulus identification and response selection. Interference suppression focuses on the ability to filter out irrelevant information and to selectively attend to the stimulus attributes that are needed to accomplish the task. This is typically tested in tasks where distractor stimuli may interfere with the target stimulus, such as in an Eriksen Flanker task, where the direction of surrounding arrows can be either similar or different from that of a target arrow (Eriksen & Eriksen, 1974). Good examples of tasks that require response inhibition are stop signal tasks, during which an intended response is aborted by a stop signal (see, for a review, Verbruggen & Logan, 2008).

Is it possible to differentiate the functional involvement of the two main neural components of the anterior attentional network (Fan et al., 2002)? The Conflict Monitor Hypothesis predicts an important distinction between the functions of the ACC and the PFC. Whereas the ACC would operate as a monitor that signals the occurrence of conflicts in information processing and the need for controlled processing, the PFC supposedly subserves these processes themselves (Botvinick, Braver, Barch, Carter, & Cohen, 2001).
Chapter 1
Theory and literature review

The most critical question in studies of cognitive control in the bilingual mind is the extent of overlap between language-specific and domain-general controlled processing. If such an overlap exists, it may be expected that extensive training in bilinguals’ control abilities has implications for the plasticity and efficiency of some of the components of executive functioning (Hilchey & Klein, 2011).

1 Theoretical foundations

How are control abilities that are required in bilingual language processing related to domain-general cognitive control? In his Inhibitory Control model of lexical processing in bilinguals, Green (1998, p. 67) suggested a high degree of overlap between real-life language activities and laboratory interference tasks: “To exemplify: consider the task of translating a visually presented word. Is this not also a kind of Stroop task? Bilinguals have to avoid naming the printed word and, instead, produce a translation equivalent as a response.”

Figure 2.1 The colour word Stroop task as an example of stimulus-response ensemble type 4 (Kornblum et al., 1990). The colour of the words is the target stimulus dimension, the meaning of the word the non-target dimension. Naming a colour is easier when relevant and irrelevant dimensions lead to the same response (left) than if they lead to different responses (right).
Crucially, bilingualism-induced effects on cognitive control performance can only be explained by assuming a link between the processes of inhibition and activation that are required during mixed-language tasks and the same processes that are needed for successful conflict resolution on domain-general control tasks.

How is conflict generated in these interference tasks and what are their behavioural correlates? The Dimensional Overlap model may be helpful to answer these questions (see section 1.1).

1.1 Dimensional Overlap model (Kornblum et al., 1990)

Domain-general interference tasks are typically composed of task-relevant and task-irrelevant stimulus features. In a colour word Stroop task, for example, the colour of the words is the relevant dimension and the meaning of the word the irrelevant dimension (see Figure 2.1). According to the Dimensional Overlap model (DO model; Kornblum, Hasbroucq, & Osman, 1990), the behavioural correlates of interference tasks are determined by the overlap between task-relevant or task-irrelevant dimensions of the stimuli and the dimension of the required response (set-level determinants), and by features of the individual trials (element-level determinants).

Stimulus-response ensembles can be classified into four different ensemble types based on their set-level determinants (see Table 2.1). This taxonomy can be visualized as a continuum ranging from ensemble types that are characterized by the absence of overlap with the response dimension in both the relevant and the irrelevant stimulus dimensions (ensemble type 1) to ensemble types that show overlap in both dimensions (ensemble type 4). The colour word Stroop task is an example of a stimulus-response ensemble type 4. In this type, both relevant and irrelevant stimulus dimensions overlap with the required response. Indeed, the colour in which a colour word is presented and its meaning both overlap with the dimension of the correct response: the colour of the word (see Figure 2.1).
The DO model (Kornblum et al., 1990) posits that the processes generated by the presentation of a stimulus element will be different depending on the dimensional overlap of stimulus-response sets. The presentation of a stimulus element within an ensemble with a high degree of dimensional overlap results in two processes that succeed one another: activation and confirmation. The activation function is automatic, thus comparable to the function of a prime which automatically triggers a response. The confirmation function verifies the validity of this activation function. If the activated and required responses match, the prime will have been facilitative. If not, the activated response must be aborted and the correct programme for response execution retrieved. This will incur a behavioural interference cost in terms of lower accuracy or slower responding.

This implies thus that some elements (or trials) within stimulus-response sets are easier to process because of optimal mapping between activated and required responses. Trials on which the activated and required responses coincide are referred to as congruent trials. If there is no optimal mapping, a trial is labeled 'incongruent'. The DO model predicts that “the overall mean reaction time is faster with congruent than with incongruent mapping” (Kornblum et al., 1990, p. 256). This is logical because an incongruent trial requires two additional cognitive processes: the abortion of the automatically triggered response and the retrieval of the rule-generated response programme. The abortion stage can be referred to as activation inhibition. It is exactly this inhibition of an automatically triggered response that makes congruence effects relevant to bilingualism research. The inhibition that is required to perform target language selection in the face of joint activation of the non-target language is

<table>
<thead>
<tr>
<th>ENSEMBLE TYPE</th>
<th>ENSEMBLE DIMENSION</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relevant</td>
<td>Irrelevant</td>
</tr>
<tr>
<td>1</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2.1 Classification of stimulus-response ensembles by dimensional overlap on the relevant and irrelevant Dimensions. The colour of the rows refers to whether (green) or not (red) these ensemble types have been used in studies of bilingualism. Adapted from Kornblum et al. (1990).
supposed to be similar to the inhibition that is needed to abort the automatic prime in a colour word Stroop task (Green, 1998).

Not all stimulus-response sets lead to congruence effects. These effects will only be observed in stimulus-response sets with dimensional overlap. This hypothesis is referred to as the first major stimulus-response compatibility effect: “given a stimulus and response set, the fastest reaction time obtainable with optimal mapping is faster if the sets have dimensional overlap than if they do not” (Kornblum et al., 1990, p. 256).

Even within stimulus-response sets with dimensional overlap, differences can be found in the congruence effect. The DO model posits that the more overlap there is between relevant or irrelevant dimensions and the target response, the larger the difference will be between congruent and incongruent trials. In reality, this means that congruence-related differences will be largest for stimulus-response ensemble types 4. The difference between ensemble types 2 and 3 is not supposed to have an effect: “the effects of varying dimensional overlap or mapping with irrelevant dimensions are similar to those with relevant dimensions” (Kornblum et al., 1990, p. 256; see Table 2.1).

The size of the congruence effect does not only depend on the task features (set-level determinants) but also on the features of individual trials (element-level determinants). More specifically, the congruence effect is modulated by the features of the previous trial(s). Kornblum et al. (1990, p. 256) states that “the difference between congruent and incongruent mapping is greater for nonrepetitions than for repetitions”. Within-task modulations of congruence effects that depend on the occurrence of previous conflict are referred to as sequential effects (Hommel, Proctor, & Vu, 2004).
These sequential effects may be caused by the congruence of the previous trials. One example is the Gratton-effect. This refers to the finding that behavioural correlates of congruence effects are larger for incongruent trials that are preceded by a congruent trial than for those preceded by another incongruent trial. This effect was first found on the Flanker task (Gratton, Coles, & Donchin, 1992) and later replicated for the Simon (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002) and Stroop tasks (Kerns et al., 2004). A second example is the proportion congruence effect, which was first discovered by Tzelgov, Henik, and Berger (1992). They demonstrated that the Stroop effect was larger in a task design with more congruent than incongruent trials. Proportion congruence effects can be summarized as follows: the size of the congruence effect will increase when the percentage of incongruent trials decreases.

How can these effects be accounted for? If performance is affected by the distribution of conflict over the previous trials, certain neural processes will have to keep track of how probable the occurrence of conflict is. The exact mechanism behind these processes and its functioning was explained by the Conflict Monitoring hypothesis (Botvinick et al., 2001). This hypothesis assumes that the cognitive control system constantly monitors the level of conflict. Conflict resolution is supposedly composed of two distinct steps: first, a conflict is detected; then, behavior is adjusted on the
subsequent trial (Carter et al., 1998; Botvinick et al., 1999; Botvinick et al., 2001). These two components of conflict resolution have distinct neural correlates. Kerns (2006) found that activity in the ACC could significantly predict behavioural adjustments on subsequent trials in the Simon task; the adjustments, themselves, were associated with PFC activity.

Verguts and Notebaert (2008) proposed a conflict-modulated Hebbian learning rule. The model assumes “a conflict monitoring unit [that] calculates a running (weighted) average of conflict across trials; hence, this unit integrates priming (influence of the previous trial) and more long-lasting context effects (influence of earlier trials)” (Verguts & Notebaert, 2008, p. 520). In practice, this means that the connections between the input from the task-relevant dimension and the corresponding response units will be strengthened in function of the amount of conflict on the previous trial and of the proportion of conflict trials across the entire task context. This monitoring is also required by bilinguals in any context that requires the two languages to be held available (Costa et al., 2009).

1.2 Training effects and bilingual advantages

Studies investigating the effect of training on congruence effects have revealed a strong link between training and automaticity in interference tasks (e.g., Schneider & Shiffrin, 1977). More recently, the transfer of training effects from one measure of cognitive control to another has received attention. Millner, Jaroszewski, Chamarthi and Pizzagalli (2012) investigated behavioural and neural correlates of short-term training-induced cognitive control improvements. All participants performed a 3-day training session with pre- and post-training tests. Different cognitive control tasks were used for training and testing. Participants showed reduced congruence effects on the post-training test. Similarly, neurofunctional plasticity was observed as indicated by the reduction in neural activity underlying interference resolution.

Similar training effects can be expected in bilinguals as a result of their long-term exposure to language conflict. If language and cognitive conflict are embedded in overlapping neural circuitry, bilingualism will induce behavioural and neurofunctional plasticity in executive functioning processes. Hilchey & Klein (2011) suggested two hypotheses on the cognitive control components being affected by bilingual training effects in
non-linguistic interference tasks. The first one is called the Bilingual Inhibitory Control Advantage (BICA) and has been described as follows:

Frequent use of the inhibitory processes involved in language selection in bilinguals will result in more efficient inhibitory processes, which will confer general advantages on nonlinguistic interference tasks – that is, those requiring conflict resolution. These advantages will be reflected in reduced interference effects in bilinguals as compared to monolinguals. In other words, bilinguals should show an advantage over monolinguals on trials with response conflict (Hilchey & Klein, 2011, p. 628).

The BICA is similar to the transfer and training effects described by Millner et al. (2012): training in one type of control abilities, i.e., language control, is expected to have an impact on another type of control, i.e., general-purpose inhibitory control. The BICA predicts specific bilingual advantages on incongruent trials of interference tasks.

A second bilingual advantage is supposed to have a more general effect on executive functioning (Hilchey & Klein, 2011). The Bilingual Executive Processing Advantage (BEPA) hypothesis states that bilingual advantages are not limited to inhibitory control. Rather, this hypothesis predicts domain-general executive advantages for bilinguals, both on congruent and incongruent trials of interference tasks. The term BEPA is rather misleading because it is not executive processing (or cognitive control) as a whole which is the relevant factor being affected. Actually, congruent trials are not assumed to tap controlled cognitive processing. This means that another type of controlled cognitive processing underlies this effect.

A more accurate description of the theoretical foundation for the BEPA states that it is the result of a “more efficient monitoring processing system, in charge of evaluating the need of involving conflict resolution processes or not when a given trial is presented” (Costa et al., 2009, pp. 141-142). These monitoring processes are highly relevant for bilinguals in any mixed-language activity that requires both languages to be held available simultaneously.

How can these effects be tested? Hilchey and Klein (2011) mention three different approaches. The most common approach is to use the traditional
colour Simon task (see Figure 2.3). Participants to the Simon task are instructed to associate a certain stimulus colour with a spatial response (left or right). Stimuli can be presented on the left or the right side of the visual field. The Simon effect predicts slower response times when there is a mismatch between stimulus and response location. If, for example, the colour ‘blue’ is associated with a response on the left, a blue stimulus that appears on the right side of the screen will be processed more slowly and less accurately than an identical stimulus that appears on the left. According to the DO model, the Simon task is an example of a stimulus-response ensemble type 3 (see Table 2.1). This means that there is dimensional overlap between the irrelevant dimension (stimulus location) and the spatial response (response location). On the opposite, the relevant dimension (colour) does not show any overlap with the dimension of the required response (space). Stimulus-response ensembles of this type reveal the involuntary nature of the activation mechanism because it is only the non-target dimension that interferes with the required response. Indeed, even when participants are explicitly instructed to ignore the non-relevant dimension, response times will show a Simon effect. The mechanism behind this effect was initially described as a strong natural tendency to react towards the major source of stimulation (Simon & Rudell, 1967).

A variant of this same task that has been used in studies with bilingual participants is the ‘spatial Simon’ or ‘arrow Simon’ task (Bialystok, 2006). In this variant, the direction of arrow stimuli is the target stimulus attribute. Participants are instructed to associate the direction of the arrows to a spatial response. Stimuli can be presented on the left or the right side of the visual field. This implies that both the relevant (direction) and the irrelevant dimensions (location) show overlap with the required response (location). According to the taxonomy suggested by Kornblum et al. (1990), this would refer to a stimulus-response ensemble type 4.
A third approach to test the BICA and BEPA hypotheses has been to use the Flanker task (Eriksen & Eriksen, 1974), embedded in an Attention Network Test as the ‘executive control’ component (Fan et al., 2002). Each trial of a flanker task is composed of a central arrow surrounded by four other arrows (or flankers) that either point in the same or the opposite direction. Participants are instructed to ignore the direction of the flankers and to focus only on the target stimulus. Similar to the spatial Simon task, this is an example of stimulus-response ensemble type 4: both the relevant and the irrelevant dimensions overlap with the required response.

The following section will discuss and evaluate all studies that have used one or several of these tasks to test bilingual advantages in cognitive control. Three following questions will receive special attention. The first question is: ‘Which cognitive control component is affected by bilingualism?’ Three possible answers to this question will be discussed: inhibition (BICA), monitoring (BEPA) or congruence switching (BCSA). The second question is: ‘What type of bilingualism creates advantages in cognitive control?’ Two relevant factors are discussed: onset age of second language acquisition and language control abilities. The third question is: ‘What are the neural correlates of bilinguals’ controlled cognitive processing?’ The hypothesis has been proposed that bilingualism induces functional plasticity in executive processes by recruiting different regions than monolinguals or by altering the degree of activity in the same regions (Abutalebi et al., 2012; Bialystok et al., 2005a; Garbin et al., 2010)
2 Which cognitive control component is affected by bilingualism?

2.1 Studies showing an effect on inhibition in the Simon task

<table>
<thead>
<tr>
<th>STUDY</th>
<th>TASK</th>
<th>TRIALS (NR.) &amp; [CONG. (%)]</th>
<th>GROUPS (NR. &amp; DESCRIPTION)</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bialystok et al. (2004)</td>
<td>Colour</td>
<td>28 [50% congruent, 50% incongruent]</td>
<td>4 [2 x 2: language group (mono- and bilinguals) x age (young and old)]</td>
<td>Middle-aged and older adults</td>
</tr>
<tr>
<td>--- Study 1</td>
<td>Simon</td>
<td>192 [50% neutral; 25% con.; 25% inc.]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--- Study 2</td>
<td></td>
<td>480 [50% neut. (4 colours); 25% con./25% inc. (2 col)]</td>
<td>2 [mono- and bilinguals]</td>
<td>Middle-aged adults</td>
</tr>
<tr>
<td>--- Study 3</td>
<td></td>
<td>144 [50% congruent, 50% incongruent]</td>
<td>4 [2 x 2: language group (mono- and bilinguals) x age (young and old)]</td>
<td>Young and older adults</td>
</tr>
</tbody>
</table>

Table 2.2 Overview of studies showing a BICA in the Simon task.

The first article ever published on bilingual performance on the Simon task was composed of a number of studies that investigated the effects of age and language background on cognitive control. The first study reported in this article investigated two groups of middle-aged and older adults. Each age group was composed of 10 monolingual speakers of English living in Canada and 10 Tamil-English bilinguals living in India. Results showed an interaction effect between language group and congruence, which is indicative of a smaller Simon effect in speed and accuracy. A remarkable feature of this study was the small number of trials (only 28), which could account for the unusually high variability in response times, ranging from almost 500 milliseconds in young bilinguals to more than three seconds in old monolinguals.
A second study from the same article attempted to replicate the findings from the first study by adding three more conditions to the traditional Simon task, thereby raising the number of trials from 28 to 192. Just as in the first study, results showed a main effect of language group on the Simon effect in terms of speed. The most significant drawback of these studies is that the groups not only differed in their language background but also in their ethnic origins, with the monolingual group being born and raised in Canada and the bilingual one in India.

This limitation was overcome in a third study. All participants, irrespective of their language background, lived in the same Canadian community: they were either English-speaking monolinguals or English-French bilinguals. The length of the Simon task was significantly raised to 240 trials spread over ten blocks. The aim of this study was to examine whether performance between bilinguals and monolinguals would converge after sufficient practice. In contrast to the previous studies, no analyses were conducted on the mean response times for congruent and incongruent trials. Instead, the Simon effect was calculated for each individual by subtracting mean response times on the congruent condition from those on the incongruent condition. This analysis showed main effects of language and of block and an interaction effect between these two factors. This means that bilinguals’ faster responding was only detectable in certain portions of the task, more specifically at the beginning of the task (see Figure 2.4). These results, thus,
indicate that the bilingual advantage disappears after sufficient practice for monolinguals.

Finally, a fourth study that reported significant congruence-related differences was conducted in English-Spanish bilingual young and old adults and English monolingual controls from South Florida, United States (Salvatierra & Rosselli, 2010). Improved performance related to bilingualism was restricted to the group of older adults, where the bilinguals showed smaller response latencies for the incongruent trials than the monolingual controls.

Figure 2.5 The BICA, as indicated by lower response times and a more modest Simon effect are only visible in the first blocks of a two-colour Simon task, but disappear after sufficient task practice. Source: Bialystok et al. (2004, p. 300).
2.2 Studies showing an effect on monitoring in the Simon task

<table>
<thead>
<tr>
<th>STUDY</th>
<th>TASK</th>
<th>TRIALS (NR.) &amp; [CONG. (%)]</th>
<th>GROUPS (NR. &amp; DESCRIPTION)</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bialystok et al. (2005b)</strong></td>
<td>Colour Simon</td>
<td>36 [50% con.; 50% inc.]</td>
<td>2 [mono- and bilinguals]</td>
<td>5</td>
</tr>
<tr>
<td>--- Study 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--- Study 2</td>
<td></td>
<td>40 [50% con.; 50% inc.]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--- Study 3</td>
<td></td>
<td>80 [50% con.; 50% inc.] + neutral trials</td>
<td></td>
<td>20-30</td>
</tr>
<tr>
<td>--- Study 4</td>
<td></td>
<td>56 [50% con.; 50% inc.]</td>
<td>4 [2 x 2: language group (mono- and bilinguals) x age (young and old adults)]</td>
<td>30-80</td>
</tr>
<tr>
<td>--- Study 5</td>
<td></td>
<td>96 [50% neut.; 25% con.; 25% inc.]</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bialystok (2006)</strong></td>
<td>Colour &amp; arrow Simon</td>
<td>480 [33% neut.; 33% con.; 33% inc.]</td>
<td>4 [2 x 2: language group (mono- and bilinguals) x gaming experience [player vs non-player]]</td>
<td>M=22</td>
</tr>
<tr>
<td><strong>Emmorey et al. (2008)</strong></td>
<td>Flanker</td>
<td>96 [50% con.; 50% inc.]</td>
<td>3 [monolingual, unimodal and bimodal bilinguals]</td>
<td>M=48</td>
</tr>
<tr>
<td><strong>Martin-Rhee &amp; Bialystok 2008</strong></td>
<td>Colour Simon</td>
<td>Not mentioned [50% con.; 50% inc.]</td>
<td>2 [mono- and bilinguals]</td>
<td>M=5</td>
</tr>
<tr>
<td>--- Study 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--- Study 2</td>
<td></td>
<td>40 [52.5% con.; 47.5% inc.]</td>
<td></td>
<td>M=4.5</td>
</tr>
<tr>
<td>--- Study 3</td>
<td>Arrow Simon</td>
<td>48 [50% con.; 50% inc.]</td>
<td></td>
<td>M=8</td>
</tr>
</tbody>
</table>

Table 2.3 Overview of studies showing a BEPA in different variants of the Simon task.

The BEPA (Hilchey & Klein, 2011; see section 1.2) refers to improved performance for bilinguals, both on congruent and incongruent trials of interference tasks (see Figure 2.4). Statistically, it is made evident by a main effect of group, combined with the absence of an interaction effect between group and congruence (Paap & Greenberg, 2013).
In a follow-up study to Bialystok et al. (2004), the same researchers intended to investigate improved bilingual inhibitory control in five studies with participants from different age groups (Bialystok et al., 2005b). Participants to the first two studies were five year old balanced English-French bilinguals and English-speaking monolinguals. Both studies used a traditional two-colour Simon task. The first study design only consisted of 36 trials divided among two conditions. Results showed equally improved performance in bilinguals on congruent and incongruent trials. The second study replicated these findings in a design with 40 trials.

The following three studies showed an interaction between development and the BEPA. While no differences between monolinguals and bilinguals were seen in a group of young adults (third study), they were visible in groups of older (fourth study, age 60-80) and middle-aged adults (fifth study, age 30-60). It was concluded that the effect of bilingualism is not present when individuals are at the top of their attentional abilities.

The exact nature of the BEPA was further tested in bilingual young adults by manipulating the need for monitoring (Bialystok, 2006). Two conditions were included: a low monitoring condition with 15 switches between congruent and incongruent trials, and a high monitoring condition with 28 switches. Main effects of bilingualism were only observed on response times in the high monitoring variant of the arrow task. This clearly reveals the explicit link between enhanced monitoring skills and improved overall performance.

Martin-Rhee & Bialystok (2008) further explored the impact of slight differences in the properties of a Simon task by manipulating the interval between stimulus presentation and response. The insertion of a delay results in lower processing demands. As a consequence, it was expected that the bilingual advantage seen in the traditional or immediate version of the Simon task would be reduced in the short delay version and even eliminated in the long delay variant. Results of the first study with five year old children as participants only partly confirmed this hypothesis. A bilingual advantage for speed was present in the classical version, but absent in the other two. In a second study with even younger children, the same pattern of improved global performance could be observed on a no-delay task. Finally, the third study of this article revealed significant
Neural and behavioural correlates of cognitive control

differences between mono- and bilinguals in colour and arrow versions of the Simon task.

Emmorey et al. (2008) showed that the effects on monitoring are only visible in individuals with two languages in the same modality. Three groups of adults were compared on conflict processing in the Flanker task: monolinguals, unimodal bilinguals and bimodal bilinguals. This last group was composed of hearing individuals born to deaf parents, who acquired both English and American Sign Language in their first year of life. The unimodal bilinguals turned out to outperform both the monolinguals and bimodal bilinguals, who did not differ from each other. Again, it should be noted that the bilingual group was composed of individuals with a migration background.

2.3 Studies showing effects on inhibition and monitoring in the Flanker task

<table>
<thead>
<tr>
<th>STUDY</th>
<th>TASK</th>
<th>TRIALS (NR.) &amp; [CONG. (%)]</th>
<th>GROUPS (NR. &amp; DESCRIPTION)</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costa et al. (2008)</td>
<td>ANT</td>
<td>288 [33% neut.; 33% con.; 33% inc.]</td>
<td>2 [mono- &amp; bilinguals]</td>
<td>Young adults</td>
</tr>
<tr>
<td>Costa et al. (2009)</td>
<td>---Experiment 1</td>
<td>ANT</td>
<td>288 [2 variants: 8% con.; 92% inc. &amp; 92% con.; 8% inc.]</td>
<td>2 [mono- &amp; bilinguals]</td>
</tr>
<tr>
<td></td>
<td>---Experiment 2</td>
<td>288 [2 variants: 75% con.; 25% inc. &amp; 50% con.; 50% inc.]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.4 Overview of studies showing BICA & BEPA in the Flanker task.

Costa et al. (2008) investigated bilingual advantages by using an Attention Network Test (Fan et al., 2002). The attention network is composed of three components that are subserved by different neural systems (Posner & Petersen, 1990). The first two components of the network, alerting and orienting, are part of a posterior attentional network. The third one, executive functioning, is supposedly embedded in an anterior attentional network, including the PFC and ACC. The Attentional Network Test is a combination of a cue reaction time task (Posner, 1980) and a Flanker task (Eriksen & Eriksen, 1974).
The bilingual effects on inhibition and monitoring were tested in a sample of 200 Spanish monolingual and Spanish-Catalan bilingual participants. The bilingual group was composed of simultaneous and balanced bilinguals who were educated in both languages and who lived in the bilingual city of Barcelona. Monolinguals lived in a monolingual society.

Results showed a main effect of language group, indicating faster responses for congruent and incongruent trials, and an interaction effect between language group and congruence, which is indicative of a smaller conflict effect for the bilingual group. In addition, a triple interaction effect was found between language group, congruence, and block, with the bilingual advantage only visible in the first two blocks and not in the third. This last finding is a demonstration of practice effects: after sufficient within-task practice, monolinguals will score as well on conflict resolution as bilinguals (Bialystok et al., 2004).

Unexpectedly, the interaction between alerting and language group also reached significance, revealing that bilinguals benefited more from the presence of an alerting cue. The alerting advantage was explained by the complex interaction between the different components of the attention network. In fact, the magnitude of the alerting effect was negatively correlated to the conflict effect. This means that the more an individual took benefit of an alerting cue, the smaller the congruence-related differences became. It might thus be that the advantage on alerting is a side-effect from the bilingual effect on inhibition.

Costa et al. (2009) further tested the effects on inhibition and monitoring in several variants of the Flanker task. The first two variants were composed of 8% of congruent or of incongruent trials, respectively (low-monitoring or LM task). In the third variant, the ratio was 75% of incongruent to 25% of congruent trials (intermediate-monitoring or IM task). Finally, a 50-50 distribution was employed in the fourth variant (high-monitoring or HM task). Each of the task variants was made up of three different blocks. Overall shorter response latencies were observed in all three blocks of the HM task, in the first block of the IM task and not at all in the LM tasks. This confirms the connection between congruence mixing and the extent of the bilingual advantage. In practice, tasks with high monitoring requirements and many congruence switches are more prone to show bilingual advantages on overall performance in interference tasks.
The effects on inhibition showed a totally different pattern because the advantage on the conflict effect was only visible in the first block of the IM version of the Simon task but not at all in the HM task. It was assumed, thus, that both congruence mixing and a considerable degree (more than 50%) of incongruent trials are required to observe an effect on inhibition. Indeed, this explains its presence in the IM task and its absence in the LM (no congruence mixing) and HM (no considerable degree of incongruent trials) tasks. In addition, the absence of an effect on inhibition in the second and the third block of the HM task demonstrates again that practice interacts with this effect (Bialystok et al., 2004).

Interestingly, the authors of this study attribute this advantage to the monitoring processes that are needed in code-switching or mixed-language contexts. Three sociolinguistic factors are expected to modulate bilingual effects on monitoring. The first factor is the functional distribution of languages in society. It is proposed that bilingual speakers in diglossic sociolinguistic environments will not show monitoring effects. First described in 1959, diglossia refers to a situation in which two closely related languages are used by a single language community (Ferguson, 1959). Typically, diglossia is characterized by functional distribution. This means that each of the languages fulfills different roles, such as one language being spoken in formal settings and another one in informal settings (Schiffman, 1997). Logically, a diglossic situation will not raise the possibilities for bilinguals to engage in two-language conversations; hence, little monitoring will be needed.

A second social factor that might affect the need for language monitoring in bilingual interactions is the degree of individual bilingualism in a society. A high percentage of proficient bilinguals will raise the opportunities for bilingual conversations and the need for monitoring. Third, it is suggested that the degree of similarity between two languages even further maximizes the opportunities for bilingual conversations.

All three criteria are met in the Catalan sociolinguistic environment: Catalan and Spanish are used in the same contexts, the languages are typologically related and they are spoken and understood by the majority of the population (Vila I Moreno, Vial, & Galindo, 2004).
2.4 A Bilingual Congruence Switching Advantage

The size of the cognitive conflict effect has been shown to depend on the congruence of the previous trial. This is commonly referred to as the Gratton-effect, which predicts that incongruent trials will show larger response latencies if they are preceded by a congruent instead of an incongruent trial (Gratton et al., 1992). The direction of the switch also plays a role. In language switching tasks, higher costs are found for switching from the most difficult (L2) to the least difficult trials (L1) than the other way around (Meuter & Allport, 1999). Applied to the Flanker task, this would imply that incongruent to congruent switches would be more difficult than congruent to incongruent switches. During incongruent trials, the automatic tendency to respond to the flankers has to be inhibited. Switching from an incongruent to a congruent trial involves the deactivation of this suppression, a process which will incur a significant switching cost.

Costa et al. (2008) tested the effect of bilingualism on congruence switching by making a distinction between congruence switch and congruence repeat trials. The results showed a bilingual congruence switching advantage.
(BCSA) with larger switching costs for monolinguals than for bilinguals. When these trials were partitioned according to the congruence of the previous trial, bilinguals only showed an advantage on switches into congruent trials. These results showed that congruence switching might be the relevant process that underlies bilingual effects on monitoring.

### 2.5 Studies showing no bilingual advantages

<table>
<thead>
<tr>
<th>STUDY</th>
<th>TASK</th>
<th>TRIALS (NR.) &amp; [CONG. (%)]</th>
<th>GROUPS (NR. &amp; DESCRIPTION)</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bialystok et al. (2005a)</td>
<td>Colour Simon</td>
<td>624 [33% neut.; 33% con.; 33% inc.]</td>
<td>3 [monolinguals, English/French bilinguals, English/Cantonese bilinguals]</td>
<td>22-36</td>
</tr>
<tr>
<td>Luk et al. (2010)</td>
<td>Flanker</td>
<td>160 [20% baseline, 20% neutral; 20% con.; 20% inc.; 20% no-go]</td>
<td>2 [mono- and bilinguals]</td>
<td>20-22</td>
</tr>
<tr>
<td>Paap &amp; Greenberg (2013)</td>
<td>Colour Simon</td>
<td>40 [50% con.; 50% inc.]</td>
<td>2 [mono- and bilinguals]</td>
<td>Young adults</td>
</tr>
</tbody>
</table>

Table 2.5 Overview of studies showing no bilingual advantages.

The existence of bilingual advantages in cognitive control has recently been challenged by a number of articles with the following provocative titles: ‘There is no coherent evidence for a bilingual advantage in executive functioning’ (Paap & Greenberg, 2013) or ‘On the bilingual advantage in conflict processing: Now you see it, then you don’t’ (Costa et al., 2009). This section discusses a number of studies that failed to detect bilingual advantages of any nature.
Bialystok et al. (2005a) compared two groups of bilinguals with different ethnic origins to a group of monolingual controls. All participants were young adults who lived in Canada. Results showed a group effect with a group of Cantonese-English bilinguals outperforming both monolinguals and French-English bilinguals on global Simon task response times. No differences were seen between the monolinguals and the French-English bilinguals. The only between-subjects variable thus that was found to dissociate performance was not language background but ethnic origin.

Morton & Harper (2007) intended to investigate the Simon effect in two groups of mono- and bilingual children who had an equal socioeconomic status. Participants were English-French bilingual children who grew up in Ontario, Canada. The recruited children scored equally on French and English receptive vocabulary and their scores were equal to those of monolingual controls. Although the task features of the design did not differ from those employed in two previous studies that reported bilingual advantages (Bialystok et al., 2004; Bialystok et al., 2005b), no between-group effects were found. This is highly relevant because this study tested an age group in which two other studies had found significant differences (Bialystok et al., 2005b; Martin-Rhee & Bialystok, 2008). A similar null effect was observed in two studies in which groups of mono- and bilingual Canadian young adults were compared on three different executive functioning tasks (Kousaie & Phillips, 2012) or on a Flanker task (Luk, Anderson, Craik, Grady, & Bialystok, 2010).

Migration and socioeconomic differences have been proposed as confounding variables that might have distorted results in previous studies (Morton & Harper, 2007; Kousaie & Phillips, 2012). While it is true that some of Bialystok’s studies investigated mono- and bilingual samples from different ethnic origins and socioeconomic backgrounds (Bialystok et al., 2004; Bialystok et al., 2005b), it cannot be denied that bilingual advantages were also found in other studies that controlled for these two intervening variables (e.g., Bialystok et al., 2004; Bialystok, 2009).

The existence of BICA and BEPA was severely criticized in a recent article that reported three studies in which bilinguals were compared to monolinguals on 15 indicators of executive functioning, including a Simon task and an Eriksen Flanker task (Paap & Greenberg, 2013). Participants were young adult psychology students who rated their proficiency in a
second language at least as advanced intermediate. Only in one of the three studies a significant interaction effect was found between congruence and group in the Simon task. Curiously, the results indicated a bilingual disadvantage rather than an advantage. However, after controlling for parental educational level, none of the group effects survived. Besides, no main group effects were found. A same pattern of results was detected in the Flanker task: no significant differences were found that favoured the bilingual group. In fact, each of the blocks showed small but non-significant advantages for the monolinguals.

As a conclusion, Paap & Greenberg (2013) discard the theoretical foundations for assuming an overlap between language control requirements and bilingual advantages on cognitive control. Even though bilinguals need language control for monitoring their communication environment, for enabling fluid language switching, and for the inhibitory control needed to suppress translation equivalents in the non-target language (Dijkstra & van Heuven, 1998), each of these three components of controlled language is also needed in other language interactions, even between monolinguals. One might think about the need to monitor environmental signals for turn-taking, sarcasm, changes in register, etc. Paap and Greenberg (2013, p. 256) conclude that “fluent bilinguals have additional needs for monitoring, switching, and inhibitory control, but these unique requirements may not be substantial enough to generate group differences in cognitive control”.

While it is true that the above mentioned studies could not replicate earlier findings of bilingual advantages in controlled processing by using the same methodology, it is unfair to ignore all evidence in favour of enhanced performance in bilinguals. This is certainly the case if these studies gave a proper explanation on why they found effects and others did not, such as Costa et al.’s (2009) sociolinguistic account of bilingual advantages. It can even be argued that a one-sided psychological view on controlled processing in bilinguals, as the one given by Paap & Greenberg (2013) fails to grasp the full complexity of bilingual behavior in real life and its possible effects on laboratory contexts. Therefore, a comprehensive view of bilingualism-induced advantages has to be put forward. This perspective should combine the psychological and sociological aspects of controlled processing in bilinguals (see Part Four).
3 What type of bilingualism creates advantages in cognitive control?

Studies that merely compare bilingual to monolingual groups have not generated clear results as to the presence and underlying mechanisms of bilingual advantages in controlled processing. Therefore, individual variability within bilingual populations should be taken into account. This section discusses two relevant factors that might have an effect on the presence of cognitive control advantages in bilingual populations: the onset age of second language acquisition and language control abilities.

3.1 Early bilingualism

<table>
<thead>
<tr>
<th>STUDY</th>
<th>TASK</th>
<th>TRIALS (NR.) &amp; [CONG. (%)]</th>
<th>GROUPS (NR. &amp; DESCRIPTION)</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carlson &amp; Meltzoff (2008)</td>
<td>ANT</td>
<td>48 [33% neut.; 33% con.; 33% inc.]</td>
<td>3 [simultaneous bilinguals, sequential bilinguals, monolinguals]</td>
<td>6</td>
</tr>
<tr>
<td>Luk et al. (2011b)</td>
<td>Flanker task</td>
<td>96 [33% neut.; 33% con.; 33% inc.]</td>
<td>3 [early bilinguals, late bilinguals, monolinguals]</td>
<td>$M = 21$</td>
</tr>
<tr>
<td>Poarch &amp; van Hell (2012)</td>
<td>Colour Simon task</td>
<td>126 [33% neut.; 33% con.; 33% inc.]</td>
<td>4 [monolinguals, L2 learners, balanced bilinguals, balanced bilingual L3 learners]</td>
<td>6-7</td>
</tr>
<tr>
<td></td>
<td>ANT</td>
<td>144 [33% neut.; 33% con.; 33% inc.]</td>
<td></td>
<td>7-8</td>
</tr>
<tr>
<td>Tao et al. (2011)</td>
<td>ANT</td>
<td>288 [50% con.; 50% inc.]</td>
<td>3 [early bilinguals, late bilinguals, monolinguals]</td>
<td>$M = 20$</td>
</tr>
</tbody>
</table>

*Table 2.6 Overview of studies that have tested the early bilingualism effect in conflict tasks.*

If bilingualism has a positive effect on executive functioning, it may be expected that a certain amount of bilingual exposure is needed to observe the assumed advantage. Logically, this difference will depend on the starting age of exposure to multiple languages. The *early bilingualism effect hypothesis* posits that the bilingual effect will be higher in bilinguals who started actively using more than one language early in life. This hypothesis is in line with the ample literature on age of acquisition effects in the field of language and literacy development (Kovelman, Baker, & Petitto, 2008; Sundara, Polka, & Genesee, 2006; Uccelli & Páez, 2007).
One of the challenges in studying age effects is to isolate this factor from other potentially confounding factors such as proficiency, accumulated exposure and manner of acquisition. Early bilinguals are most often more proficient in their second language, they have had more exposure to it and have acquired it implicitly.

Luk et al. (2011b) tested the early bilingualism effect on cognitive control by comparing two groups of early and late bilinguals to each other and to age-matched monolingual controls. Critical for distinguishing the two groups was the age at which they began using both languages actively and regularly on a daily basis. The onset age of active bilingualism was age five for early bilinguals and age sixteen for late bilinguals. All participants performed a Flanker task (Eriksen & Eriksen, 1974). A significant interaction effect was found between trial type and group with better scores for the early bilinguals, specifically on incongruent trials. In addition, conflict resolution abilities were measured by calculating the Flanker effect. Again, significant differences were found: early bilinguals showed the lowest costs and the two other groups were not different from each other. Direct relationships between the measures of language use and cognitive control were investigated using correlation analyses. Interestingly, onset age of active bilingualism correlated positively with the Flanker effect, indicating higher conflict resolution skills for individuals who had been using their two languages for a longer period of time.

A major drawback of this study was that age and proficiency were not isolated from each other. Onset age of active bilingualism turned out to correlate negatively with proficiency scores on an English receptive vocabulary test (Dunn & Dunn, 1997). Even more alarming were the massive differences in migration age between the two groups. Nearly 80% of the late bilinguals reported other countries than Canada as their birthplaces. On average, they had only lived in Canada for six years. In contrast, less than 50% of the early bilinguals were born outside of Canada with a mean stay in the host country for about thirteen years. For late bilinguals, the age of migration (15.2 years) was to a large extent confounded with the onset age of active bilingualism (15.9 years), showing a tremendous difference with early bilinguals (age of immigration around age eight).
Two conclusions come out of this study. First, the age of second language acquisition determines the presence of a bilingual advantage in cognitive control. This validates the *early bilingualism effect hypothesis*. Importantly, late bilinguals did not show any difference with monolingual controls, thereby restricting the effects on inhibition and monitoring to early bilinguals only. This conclusion is challenged, though, by the fact that linguistic variables such as second language proficiency, balanced bilingualism and manner of acquisition, and the extra-linguistic variable of time spent in the host country were not controlled for.

The impact of differences in proficiency was further shown by another study that recruited two groups of early and late bilinguals (Tao, Marzecova, Taft, Asanowicz, & Wodniecka, 2011). Both groups had a significantly lower conflict cost in a Flanker task than a monolingual population. In addition, the late bilinguals obtained a higher accuracy rate on the Flanker task than the early bilinguals, which is indicative of a negative instead of a positive early bilingualism effect. However, when differences in L1 and L2 proficiency levels were controlled for, the (negative) early bilingualism effect seemed to disappear.

At what age do age-related effects start to manifest themselves? Carlson & Meltzoff (2008) administered the Attention Network Test (ANT) as part of an extensive test battery to two groups of bilingual six year old children and a group of monolingual controls. A first bilingual group was composed of Spanish-English bilinguals who had been simultaneously exposed to both languages from birth onwards. The second bilingual group was composed of L2 learners who were enrolled in an immersion programme. These children came from English monolingual families and received instruction in Spanish or Japanese for half of the day. At the time of testing, these children had received six months of instruction in a second language. This means that age of acquisition (birth for the first group and age five for the second group) and manner of acquisition (home and community versus classroom context) were confounded.

Scores on an English picture vocabulary test revealed lower scores for the simultaneous bilingual group than for the immersion and monolingual groups, who did not differ from each other. Socioeconomic variables also showed differences: the median level of parental education was lower for the simultaneous bilinguals (high school) than for the immersion and
control groups (college). Furthermore, the average annual family income lay three times lower for the simultaneous bilingual than for the other two groups. It can be concluded that on a wide range of measures thought to have an impact on executive functioning, the group of simultaneous bilinguals scored significantly lower than the two other groups.

Despite these differences, statistical analyses on the raw scores did not reveal any significant differences, neither for the ANT nor for the other measures of executive functioning. Subsequently, potentially confounding factors such as age, verbal ability and parental education levels were added as covariates to the statistical model. Higher scores for the simultaneous bilinguals were found on three measures of executive functioning: short-term memory, non-verbal intelligence and task switching. It was proposed that age-related effects start to manifest themselves at an age as young as six years old. However, the absence of any advantage on the ANT seems to reject this claim.

A fourth study that tested the early bilingualism effect only reported an advantage for early trilinguals but not for bilinguals (Poarch & van Hell, 2012). All participants were five to eight year old children who were born and lived in Frankfurt, Germany. They were divided into four distinct groups: German-speaking monolinguals, English-German balanced bilinguals, L2 learners of English and balanced trilinguals. Test scores on grammatical proficiency in German and English revealed equal proficiency for these two languages in the groups of bi- and trilinguals. The L2 learners, in contrast, were less proficient in English than in German. Results of the Simon task showed an interaction effect between congruence and language group. Post-hoc analyses revealed that monolinguals displayed a significantly larger Simon effect in response times than trilinguals. None of the other pairwise group comparisons, such as between balanced and non-balanced bilinguals, reached significance. Results on the ANT showed enhanced conflict resolution for trilinguals over monolinguals and unbalanced L2 learners (see Figure 2.7).

This breakthrough study was the first to show that adding a third language to the bilingual’s linguistic repertoire can have a beneficial effect on the executive functioning system and that this effect already manifests itself at a very young age. Furthermore, it confirmed the finding that balanced bilinguals might outperform non-balanced bilinguals on a Flanker task (Luk
et al., 2011b; see Figure 2.7) but not on a Simon task. Nevertheless, this study had a similar limitation as the first one mentioned in this section. Half of the trilingual participants spoke at least one and possibly two other languages than the autochthonous language (German), which means that ethnic origin or migration context might have been a confounding variable.

Figure 2.7 Effect magnitudes in the ANT across three bilingual populations. Error bars represent standard errors. Note the specific effect on inhibition (incongruent trials) with a larger difference between congruent and incongruent trials for unbalanced L2 learners than for bilinguals and trilinguals who did not differ from each other. Source: Poarch & van Hell (2012, p. 546).

3.2 Language control

If constant language management is responsible for bilingual advantages in cognitive control (Hilchey & Klein, 2011), the individual variability in bilinguals’ language control abilities might explain why the advantage is only infrequently seen. This might be called the language control effect hypothesis. Six studies are discussed in this section. Using a within-group analysis approach, three studies have provided evidence for a direct connection between language and cognitive control (Linck et al., 2012;
Rodriguez-Fornells et al., 2011; Soveri, Rodriguez-Fornells and Laine, 2011). Three other studies have compared performance on cognitive control tasks in bilingual populations that were grouped according to their language control abilities (Festman, Rodriguez-Fornells, & Münte, 2010; Festman & Münte, 2012; Prior & Gollan, 2011).

Establishing the link between language and cognitive control using within-group analyses

Linck et al. (2012) investigated the overlap between domain-general and language-specific controlled processing by comparing scores on a three-language picture naming task and a Simon task. Participants were English-born childhood learners of French who started being exposed to a third language in early adulthood. Self-ratings of linguistic proficiency and verbal fluency measures revealed significant differences between all possible language combinations. Language control was established by measuring switching costs in a trilingual picture naming task. For each individual trial, the language of the current and the previous trial were plotted in a factorial design. Two important effects were found: first, a smaller Simon effect predicted faster response times on L3 naming, but not on L1 and L2 naming, irrespective of whether the trial was a switch trial or not. Second, improved inhibitory control was related to smaller switching costs into L1, but not into L2 or L3. Adding the language of the previous trial to the model revealed that both switching costs from L2 and L3 into L1, i.e., L2 to L1 and L3 to L1 were positively affected by inhibitory control. Furthermore, inhibition skills predicted switching costs from L1 to L3, but not from L2 to L3.

These results seem to validate the notion that the cognitive control network is most critically needed when switching into the dominant language (Green, 1998), because that language system requires most cognitive effort to be activated again after it was turned off in the previous trial (Meuter & Allport, 1999). The observation that switching into L3 is only dependent on controlled inhibition for switches from L1 but not from L2 might be explained by the more extensive proficiency levels between L1 and L3 than between L2 and L3. Finally, the finding that overall L3 naming was affected, both for language repeat and language switch trials, might be indicative of a sustained reliance on cognitive control abilities when dealing with a low proficient language. Indeed, functional neuroimaging of low-
proficient speech production or reception has revealed extensive activity in regions involved in attentional networks such as the PFC or subcortical structures (e.g., Abutalebi et al., 2013a).

These results shed light on how better controlled inhibition manifests itself in language control tasks. Higher controlled inhibition abilities do not seem to involve more deactivation of lexical items. If that were the case, the inhibition of a higher amount of L1 lexical items during L2 or L3 naming would result in higher switch costs into L1 in individuals with above average inhibitory control skills. Rather, better inhibitors turn out to have a more efficient system that can rapidly switch off lexical competitors. This effect is most prominent if there are large differences in proficiency levels between the languages.

This study was innovative in that it was the first to show the correlation between individual scores on cognitive and language control measures. However, this study only dealt with one very specific form of multilingualism: all participants spoke one language at home (English) and were enrolled in L2 (French) and L3 (Spanish) language courses. The onset
age of acquisition was around age seven for L2 because of compulsory French classes in Canadian public schools, and around age seventeen for Spanish. Unfortunately, no additional information was given about the potential individual variability in extracurricular exposure to these languages. Furthermore, no connection was made between differences in L2 and L3 proficiency with the switching costs from and into these languages. This would have been highly relevant since it was shown that inhibitory control effects were most prominent in the least proficient language and they were dependent on the differences in L1 and L3 levels of proficiency. Moreover, L1 to L2 switch costs turned out to show a negative (but non-significant) relationship with the Simon effect (see Figure 2.8).

The generalizability of a clear connection between inhibitory skills and language switching was challenged by a study that adopted a similar within-group analysis approach (Soveri et al., 2011). In contrast to Linck et al. (2012), the participants to this study were simultaneous bilinguals with balanced levels of L1 and L2 proficiency. They were asked to fill out a language switching questionnaire and their scores were correlated to performance on a wide range of different executive functioning measures, including Simon, Flanker and task switching paradigms. Only mixing costs in a task switching paradigm but not conflict costs in interference tasks were affected by the reported frequency of language switching. This study thus clearly shows that the language control effect may manifest itself differently for simultaneous and sequential bilinguals.

Rodriguez-Fornells et al. (2011) developed a bilingual switching questionnaire in order to test the language control effect hypothesis in a large sample of Spanish-Catalan bilingual university students, who were grouped into simultaneous bilinguals, Spanish-dominant and Catalan-dominant bilinguals. In this study, language control was operationalized as self-assessment on language switching behaviour. Language switching was decomposed into four different constructs: switching to L1, switching to L2, contextual switching and unintentional switching. It should be noted that even though the linguistic background of the individuals varied widely with most participants only using one language at home (Spanish or Catalan), the term L1 was systematically used to refer to Spanish and L2 to Catalan. As could be expected, the ‘switching to L1’ component was positively correlated to Spanish proficiency but negatively to Catalan skills. The
reverse pattern was observed for the ‘switching to L2’ construct: the more proficient an individual was in Catalan, the more switches were made to that language.

The *language control effect hypothesis* was tested by evaluating the percentage of common variance between self-assessment of the behavioural switching patterns and different executive measures including a stop signal paradigm, verbal fluency and two interference tasks: a non-verbal Flanker task and a verbal colour word Stroop task. A positive correlation was detected between ‘switching to L1’ and verbal fluency. In contrast, verbal fluency correlated negatively with ‘switching to L2’. Again, these differences might rather reflect differences in vocabulary size than executive functioning variability because verbal fluency was only measured in Spanish (L1).

Further, ‘switching to L2’ correlated negatively with response times and error rates on incongruent trials of the colour word Stroop task, i.e., those trials where the colour name and the hue were different (e.g., ‘green’ in red). This does not imply, though, that ‘L2 switches’ would have a negative influence on executive functioning because no effect was seen on the only purely non-verbal measure of executive functioning: the Flanker task. For both executive tasks, it might be that the observed negative correlation between self-assessment of ‘L2 switching’ and cognitive control scores is merely related to lower proficiency in the instruction and execution language. This conclusion is corroborated by the negative correlation between ‘L2 switching’ and L1 proficiency, the language of testing.

Interestingly, a correlation was found between self-assessment of unintentional switching and response times on the stop signal task. Thus, an individual who mixes languages unintentionally or without a clear communicative purpose is slower on a non-verbal task that taps into controlled inhibition. Though unintentional switching might be the consequence of genetic variation between bilingual individuals, also experience-induced differences were found on this variable. Most notably the unbalanced bilinguals showed a tendency towards more unintentional switches. It is logical to assume that balanced bilingualism or the simultaneous acquisition of two languages early in life raises the awareness of language switches and, as a result, leads to a cognitive control advantage.
The study thus shows that self-reported switching behaviour may explain part of the variance in bilinguals’ cognitive control skills. However, the use of verbal (Spanish-language) executive measures might have distorted the results as they showed a bias towards native speakers of Spanish. The only difference that could be attributed to language skills, independent of single-language proficiency, was the negative relationship between unintentional switches and domain-general inhibitory control. But there again, these differences were mediated by the type of bilingualism with early bilingualism leading to fewer unintentional switches than sequential bilingualism.

Comparing cognitive control in groups with different language control abilities

Festman et al. (2010) were the first to test the language control effect by comparing two groups with different language control abilities. Participants were 29 late Russian-German bilingual young adults, who were tested on their ability to resist interference from the non-target language. In order to achieve a quantitative measure of this skill, all participants took a bilingual picture naming task in which the target language was externally triggered by the colour (red or green) of a frame.

The two groups were distinguished based on the number of interference errors, or instances where the correct name was given in the non-target language. Cluster analysis was used to create two groups that were labeled as switchers and non-switchers, respectively. Switchers showed a higher number of interference errors (ranging from 10 to 20) in the bilingual picture naming task than non-switchers (ranging from none to 5). For clarity's sake switchers will be called 'low-proficient language controllers' and non-switchers 'high-proficient language controllers'.

Subsequently, all participants took a number of executive functioning tasks and intelligence tests. The 'high-proficient language controllers' showed better performance on various tasks tapping executive functioning, as well as on two verbal subtests of an intelligence test. In a later study with the same participants, Festman and Münte (2012) reported additional effects on conflict trials in a Flanker task. The operationalization of language control as the resistance to non-target language interference or controlled
language inhibition thus seemed to affect a wide variety of controlled processing aspects.

The question may be raised if the observed differences between the groups are related to pre-existing genetic differences or to environmental influences. Since executive functioning turns out to be a highly heritable psychological trait (Friedman et al., 2008), genetic factors may have an impact on the degree of resistance to language interference in the bilingual mind. The idea that experience is only a marginal player was sustained by the finding that both groups did not differ on most key demographic information such as age, gender, education, age of L2 acquisition and the number of years spent in Germany.

However, subtle variations in daily language use might also have contributed to between-group differences in language control abilities. All participants completed an extensive language background questionnaire. Two confounding variables were found. A first significant difference involved language use with siblings and relatives: whereas ‘low-proficient language controllers’ mostly used Russian with both groups, ‘high-proficient language controllers’ preferred German when interacting with their siblings and spoke each of the languages approximately half of the time to other relatives. In addition, self-rated language skills revealed that ‘low-proficient language controllers’ had significantly lower reading and writing skills in their second language.

It can easily be argued that these two interfering variables are highly relevant for understanding the language sociological basis for differences in controlled processing. Costa et al. (2009) predicted that the bilingual advantage would not manifest itself in populations with a clear-cut functional distribution of the two languages, because this would keep these bilinguals from engaging in bilingual (or mixed-language) conversations. Indeed, the German-Russian bilinguals who preferred Russian at home but German in other settings did show lower language control abilities than those individuals who used both languages at home. These language control abilities were directly associated with cognitive control performance, which shows how sociolinguistic environments may impact controlled cognitive processing.
One more point of criticism regarding this study is that the authors fail to offer a sound explanation on why the ‘high-proficient language controllers’ outperform the other group both on executive functioning and verbal intelligence tests. One explanation for this pattern of differences could be that those tasks that rely on detailed German instructions are less well performed by bilinguals with less exposure to that language. Indeed, the verbal intelligence tasks and the executive functioning measures revealed divergent results for the two groups while no similar differences were seen on tasks without a clear verbal component. Counterbalancing the instruction language could help solve the problem.

In another study, Prior & Gollan (2011) compared non-verbal task switching in the two largest bilingual groups in the United States of America: Spanish-English and Mandarin-English bilinguals. Controls were monolingual speakers of English. Bilingual participants completed an extensive questionnaire assessing language use and language switching frequency at the time of investigation and during childhood. Critically, the two bilingual groups differed significantly in their switching frequency in that the Spanish natives reported more current switching than the Chinese-born bilinguals. Differences in childhood switching behaviour did not turn out to be significant.

Even though the age of first exposure to English was identical for the two groups (at nearly 3 years of age), the Chinese natives were more proficient in English than the Spanish-English speakers, as demonstrated by verbal fluency scores. In contrast, self-ratings of L1 skills revealed that the Chinese-born bilinguals were less proficient in Mandarin than the Spanish-born bilinguals in Spanish. This was confirmed by lower L1 fluency scores in the Mandarin group than in the Spanish-born group. The accessibility of the Spanish language in California might be a valid explanation for this finding. Finally, the three groups were not matched on intelligence. A test of non-verbal reasoning revealed significantly lower scores for the Spanish-English bilinguals as compared to the two other groups.

All participants performed a non-linguistic switching task and a language switching task. The non-linguistic task switching paradigm consisted of making colour and shape judgements on visually presented stimuli; the language switching task was a trilingual digit naming task. Both tasks consisted of single- and mixed-task blocks, which allowed for a comparison
of switching (switch versus repeat trials) and mixing (mixed- versus single-
task blocks) costs. The bilingual digit naming task revealed higher overall
naming latencies for switch versus repeat trials and for mixed-language
versus single-language blocks. Interestingly, a significant interaction was
found between switching cost and language group: Spanish-English
bilinguals had significantly smaller language switching costs than
Mandarin-English speakers. In contrast, no group differences were
detected in the mixing costs.

![Figure 2.9 Correlation of Mandarin fluency scores with task switching costs for Mandarin-
English bilinguals. Note the negative correlation between proficiency in a low-exposure L1 and
non-verbal task switching costs. Source: Prior & Gollan (2011, p. 7).]

Statistical analyses of the colour-shape switching task revealed switching
costs with quicker responses on task-repeat than on task-switch trials. This
main effect was complemented by a significant interaction effect between
overall response times and language background with slower responses for
the Spanish-English bilingual speakers than for the Mandarin-English
bilinguals and the monolinguals, who scored equally well. The higher
overall latencies on a general measure of executive functioning for one
specific language group were remarkable. They could be related to the
lower socioeconomic status of the Spanish-speaking bilinguals as was
measured by the educational level of the primary and secondary caregivers.
Interestingly, response times in the native Spanish bilingual group did not
correlate with scores on the intelligence tasks, but with the educational
level of the caregivers, thereby revealing that sociological factors, rather than psychological ones, might determine the extent of the switching costs.

In a subsequent analysis, switch costs were calculated by dividing mean reaction times on task switching trials by mean reaction times on task repeat trials and these scores were entered as a dependent variable with parental educational levels as a covariate. Results revealed smaller relative switching costs for the Spanish-English group as compared to the other two, who showed equal scores. This covariate analysis was supplemented by a matching analysis in which the twenty monolinguals with the lowest parental educational level were compared to the twenty Spanish-English bilinguals with the highest parental educational level. No differences were detected on intelligence, but the bilinguals still had lower English vocabulary skills than the monolinguals. Matching these two groups resulted in equal overall response times and lower switch costs, thereby confirming the pattern that was found in the language switching task, i.e., a combination of lower switching costs with similar mixing costs.

One important conclusion of this study is that a specific pattern of language switching advantages transfers into domain-general switching advantages. Crucially, the differences between the groups in the task switching performance could be attributed to one language sociological factor, which is the higher accessibility of Spanish than Mandarin in South California due to the proximity of Mexico and the high influx of Mexican immigrants. Hence, there is a higher chance for individuals to engage in bilingual conversations, which, according to Costa et al. (2009) raises the need for language control and leads to bilingual advantages. Indeed, the Spanish-speaking group had a higher fluency in their L1 than the Mandarin-speaking group and they switched more often between their two languages.

Another interesting finding of this study was that the task switching costs in the Chinese native group were negatively correlated to the Mandarin fluency scores (see Figure 2.9). A similar correlation was not seen in the Spanish-born group. This highlights the importance of proficiency in a low-exposure L1 for predicting switching costs on a non-linguistic task. Yet, most studies on bilingual effects on cognitive control neglect the role of the first language by not including L1 language tests. A final interesting aspect of this finding is that differences in L1 levels cannot be attributed to genetic factors. This study thus shows that part of the variability in bilinguals'
cognitive control skills can only be explained by referring to experiential factors.

4 What are the neural correlates of bilinguals’ controlled cognitive processing?

A crucial question in any study of controlled processing in the bilingual mind is the extent of overlap between language-specific control and domain-general control skills. If such an overlap exists, it may be expected that bilingualism induces functional plasticity in regions of the neural language control network so that they can be used for efficient domain-general controlled processing (Abutalebi et al., 2012). This may be referred to as the Bilingual Neural Overlap hypothesis.

Bilinguals use language control areas for responding faster on a cognitive control task (Bialystok et al., 2005a)

This study used magnetoencephalography (MEG) to investigate the neural correlates of the bilingual advantage in domain-general conflict resolution. MEG is a brain mapping technique based on the registration of magnetic signals that are generated by the electrical currents naturally occurring in the brain. MEG offers a good spatial resolution because magnetic fields are less distorted by the skull than electrical signals (Cohen & Cuffin, 1983). Neural activity during a Simon task was registered in two groups of bilingual young adults (Cantonese-English and French-English) and one group of English-speaking monolingual controls (for a discussion on the behavioural data of this study, see section 2.5).

Two types of analyses were conducted on the neuroimaging data. In a first analysis, modulations of brain activity were calculated for each condition. Responses to congruent trials were associated with activity in the left dorsolateral PFC whereas responses to incongruent trials could be linked to post-central and superior frontal regions of activity. No group differences were detected.

The second analysis had as its aim to identify the neural correlates of behavioural differences in the Simon task. Across all conditions, slower
responding in the two bilingual groups was associated with more activation in right-hemispheric middle occipital, inferior parietal, and precuneus regions. Faster responding in the bilinguals was linked to more activity in largely left-hemispheric superior and middle temporal, cingulate, and superior and inferior frontal regions. Some of these regions are involved in language control. Interestingly, Peterson et al. (2002) reported no left-lateralized but bilateral activity changes in the frontal gyri for Simon task performance in monolingual participants. The match of faster responding in bilinguals specifically to left-hemispheric frontal and cingulate areas appears to corroborate the neural overlap between language and cognitive control in bilinguals. The authors concluded that “it is possible that bilingualism enhances those control processes in the left frontal lobe and makes them available for other inhibitory tasks, even nonverbal ones” (Bialystok et al., 2005a, p. 48).

Being the first study to investigate neural differences in processing a general cognitive conflict task, this research raised new hypotheses about the origin of a bilingual advantage. However, it failed to reach its initial aim to explain the bilingual advantage because differences in the pattern of neural activity were not accompanied by bilingual behavioural advantages. As mentioned previously in this chapter, the performance of the Canada-born bilinguals was more similar to monolinguals than to the Cantonese-English bilinguals.

*Bilingualism selectively affects the neural correlates of interference suppression (Luk et al., 2010)*

Luk et al. (2010) investigated the neural correlates of cognitive control performance in bilinguals. A special version of the Flanker task was used in which no/go-trials were added to the traditional congruent and incongruent trials. This allowed for a comparison between interference suppression and response inhibition (Bunge et al., 2002). Whereas incongruent trials would tap interference suppression skills, no/go-trials were linked to response inhibition. Neural between-group differences were only found on the incongruent trials. On this trial type, monolinguals activated a spatially-restricted network that was composed of the left temporal pole and left superior parietal regions. In contrast, bilinguals showed activity in a larger distributed neural network including bilateral frontal, temporal and subcortical regions. This network was also active on
no/go-trials for both groups. Behavioural data, however, did not reveal any differences.

While this study shows that neural differences between bilinguals and monolinguals only apply to the suppression of interference on incongruent trials, it does not offer any insight into the neural correlates of bilingual advantages in cognitive control. In fact, no behavioural differences were detected between the groups. Moreover, the recruitment of a widely distributed network in bilinguals and a spatially-restricted circuity in monolinguals appears to contradict the notion of more efficient neural cognitive control processing in bilinguals. Finally, the regions that were associated with incongruent trials in bilinguals do not show a clear overlap with the regions involved in controlled language processing. Whereas the widely distributed network that was active in bilinguals contained activity in some language control regions such as the bilateral IFG, the left caudate nucleus and the inferior parietal lobule, the total number of active regions amounted to fifteen, including activity in all lobes of the cerebral cortex.

**Bilingual experience changes the lateralization and localization of neural task switching (Garbin et al., 2010)**

Participants to this study were bilingual Catalan-Spanish and monolingual Spanish university students. The bilingual participants reported perfect command of both languages and frequent switching in bilingual conversations. As mentioned before, the language situation in Catalunya meets all the (socio)linguistic criteria for seeing a bilingual advantage: there is a high degree of individual multilingualism, no functional distribution and a high structural relatedness between the two languages (Costa et al., 2009).

Participants were tested on a colour-shape task switching design. Stimuli were squares and circles in red or blue. Above the figure was a written instruction that indicated whether they had to pay attention to the form or the colour. Switch trials were those instances where the previous stimulus had a different instruction (e.g., form) than the current one (e.g., colour), regardless of potential differences in colour or form. Behavioural results revealed significantly higher response times and lower accuracy scores for switch trials compared to repeat trials. Besides, a significant interaction effect between both groups and the trial type was observed on accuracy.
scores. Monolinguals showed lower accuracy when switching from one response set to another than bilinguals. The same interaction was only marginally significant for response times.

Neuroimaging results were investigated by three different kinds of analyses. *Within-group analyses* contrasting switch trials to repeat trials revealed significant bilingual activity in the left IFG. Monolinguals, in contrast, showed a larger set of active regions involving the right IFG bordering the insula, the left ACC and the left inferior parietal lobule. *Between-group analyses* were conducted using a full factorial design with reaction times and accuracy rates as covariates. In line with the within-group analyses, monolinguals showed increased activation in the right IFG. Importantly, bilinguals showed more activity in the left IFG. Finally, regression analysis was performed to investigate *performance correlates*. The mean difference between response times on switch and repeat trials was entered as a regressor. Higher switching costs were positively correlated to activity in the right IFG. Lower switching costs, on the other hand, led to increased activity in the left IFG and the left striate cortex.

The results of this study lead to the conclusion that bilingual experience changes the lateralization and localization of cognitive processes underlying cognitive control skills. Whereas traditionally right inferior frontal substrates are involved in this type of processing (Robbins, 2007), bilinguals engage the left inferior PFC, a region that is classically involved in different language control costs such as the neural L2 cost, and back- and forward switch costs (Abutalebi & Green, 2007). Interestingly, the regression analysis and the behavioural between-group differences show that activity in this region is associated to behavioural facilitation in bilinguals. In addition, the localization of cognitive control turns out to be different for bilinguals. Compared to monolinguals, bilinguals do not activate regions that are traditionally associated with task switching such as the ACC and the inferior parietal lobule.

*ACC as a common neural locus for language and cognitive control (Abutalebi et al., 2012)*

Abutalebi et al. (2012) directly compared the neural correlates of language and cognitive control in a group of German-Italian bilinguals compared to monolingual controls. Language control was measured by performance on
a bilingual picture naming task; cognitive control was tested in a Flanker task. Within-task practice effects in cognitive control were analyzed by investigating performance on two subsequent sessions of the Flanker task. Unlike previous studies (Bialystok et al., 2005a; Luk et al., 2010) significant behavioural differences were found between the groups. Most notably, the bilinguals showed practice effects with higher response time declines between the two sessions than the monolinguals (see Figure 2.10).

A combination of within-group, between-group and conjunction analyses was used to investigate the neural correlates of these behavioural differences. The ACC was designated as the main locus of controlled processing in both groups. This region was activated when language switch trials were contrasted to language repeat trials in the two-language picture naming task. In addition, the ACC was the only region of controlled processing that subserved conflict resolution on incongruent trials of the Flanker task, both in monolinguals and bilinguals. Remarkably, monolinguals recruited a larger neural network on the incongruent trials, also including other controlled processing regions such as the inferior parietal lobule. A conjunction analysis between language switching and cognitive control confirmed the ACC as a common locus for both types of controlled processing.

Between-group analyses showed that monolinguals recruited the ACC more extensively than the bilinguals on incongruent trials of the Flanker task. Surprisingly, the monolinguals did not take any advantage of neural training effects in cognitive control processing: ACC activity in the second session was even higher than in the first. This stood in stark contrast with the results in bilinguals: while they showed more ACC activity on incongruent trials in the first session, this additional activity disappeared in the second session. This was confirmed by between-group analyses: while no differences were found on the first session, the bilinguals showed less ACC activity on the second session.
Figure 2.10 Behavioural and neurofunctional effects of bilingual conflict resolution on the ACC. Only the bilinguals took advantage of Flanker training as indicated by a significant decline in the Flanker effect between session 1 and 2 (top). The monolinguals activated the ACC to a higher extent during the Flanker test (middle), and also the decline in neural activity was more outspoken for bilinguals than for monolinguals (bottom).
The results of this study prompt two important conclusions. First, there seems to be a degree of overlap between domain-specific controlled language processing and domain-general cognitive control in the bilateral ACC. Indeed, conjunction analysis of neural activity on language switch trials in a naming task and incongruent trials of a Flanker task revealed the ACC as a common locus for both task types. The function of the ACC has been extensively described in this dissertation: it signals and monitors the occurrence of conflict (Botvinick et al., 2001). A second conclusion is that bilingualism tunes the ACC for conflict processing. Whereas monolinguals showed more activity in this region during the second session of the Flanker task, bilinguals showed a significant drop in ACC activity. These within-task training effects were confirmed by the behavioural data: the declines in response times between both sessions were significant for the bilingual group, but not for the monolinguals.

To conclude, this literature review has uncovered that the PFC and the ACC are differently affected by bilingualism. While additional involvement of the PFC might facilitate cognitive control in bilinguals (Bialystok et al., 2005a; Garbin et al., 2010), the ACC is tuned by bilingualism so that less activity is needed to perform the same control task (Abutalebi et al., 2012). It is logical to assume that the frequent use of language control in bilingual language activities is responsible for this effect. The following prediction can thus be made with regards to the individual variability in bilingual populations: more activity in the PFC will be linked to behavioural facilitation in individuals with good language control abilities. In addition, good language control abilities will be connected to less activity in the ACC.
Chapter 2
Data report

The degree of behavioural and neural overlap between language-specific and domain-general controlled processing is the main focus of this chapter. This chapter reports data from two studies that intended to explore this overlap: first, a longitudinal study in simultaneous and sequential bilingual children and a group of monolingual controls; second, a cross-sectional study with the same two groups of bilingual young adults (see Table 2.7). Participants to both studies completed a couple of language and cognitive tests. This chapter reports the cognitive control data of these studies.

In addition, the overlap between scores on cognitive control and on measures of language control that were reported in the previous chapter will receive attention. Some of these language control measures were used to regroup bilingual participants according to their language control abilities (see Festman et al., 2010; Prior & Gollan, 2011), other measures were directly correlated to aspects of cognitive control performance (see Linck et al., 2012). Regarding this relationship, the following prediction was made in the previous chapter: only on those language control tasks in which the amount of controlled processing is connected to behavioural facilitation, correlations can be expected with scores on cognitive control. In practice, this means that only mixing costs and forward switch costs would explain cognitive control variability.

At the first time point of the longitudinal study with bilingual children, all participants underwent a two-colour Simon task and a numeric Stroop task inside the MRI scanner. The behavioural correlates of these two tasks and the neural correlates of the Simon task are discussed. The language data that were reported in Part One were correlated to these scores. These included back- and forward translation, an interference task and single-language tasks. In line with the predictions made in Part One, only forward translation was expected to correlate with cognitive control.

At the second time point, the same two cognitive control tasks were administered. Outside the MRI scanner, all participants did a Flanker task
embedded in an Attention Network Test. Only the behavioural correlates of these cognitive control measures are discussed. Performance on the one- and two-language phonemic verbal fluency tasks discussed in Part One was used to regroup all participants according to their language control abilities. The scores on the two-language task were also correlated to scores on cognitive control tasks. In line with predictions made in Part One, mixing costs were expected to have an effect on cognitive control. Developmental aspects of cognitive control are dealt with by comparing performance on T1 and T2.

In the cross-sectional study, all participants performed an fMRI colour Simon task. Performance on a two-language phonemic verbal fluency task was used to regroup the participants according to their language control abilities. Furthermore, backward and forward switching costs in a two-language semantic categorization task were correlated to performance on the Simon task. In line with predictions made in Part One, only forward switching costs and mixing proficiency were expected to correlate with cognitive control. The following three questions will be treated in each study: ‘Which cognitive control component is affected by bilingualism?’; ‘What type of bilingualism creates advantages in cognitive control?’ and ‘What are the neural correlates of bilinguals’ controlled cognitive processing?’

<table>
<thead>
<tr>
<th>STUDY</th>
<th>LANGUAGE</th>
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<td>Colour Simon task; Numeric Stroop task</td>
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<td>Longitudinal study – T2</td>
<td>Two-language cost by contrasting one- &amp; two-language verbal fluency</td>
<td>Colour Simon task; Numeric Stroop task; ANT</td>
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<td>Cross-sectional study</td>
<td>L1 &amp; L2 interference task; one- and two-language verbal fluency; Backward &amp; forward switching costs in two-language</td>
<td>Colour Simon task</td>
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Table 2.7 Overview of language and cognitive control measure that were used at the two time points of the longitudinal study and in the cross-sectional study. Measures that were used to regroup bilingual participants according to language control abilities are in bold.
1. Longitudinal study

The overarching aim of this study was to investigate developmental aspects of bilingualism-induced effects on cognitive control in bilingual children. This has been largely ignored in most studies; so far, no longitudinal study tracking the development of bilingual population on a longer period of time has been carried out. Yet, studies comparing bilinguals to monolinguals have shown that aging has an impact on bilingual advantages: while these effects are most prominent in older adults and young children, they tend to be attenuated in early adulthood, when individuals are at the peak of their attentional abilities (Bialystok, 2006; see, for a different view, Morton & Harper, 2007). A study of the development of control abilities in childhood may explain contradictory results in literature. Besides, it may reveal at what age bilingual advantages appear and when they disappear.

1.1 T1

Studies on the performance of bilingual children on cognitive control measures such as the Simon task have led to contradicting results. While Bialystok et al. (2005b) and Martin-Rhee and Bialystok (2008) reported a number of studies in which five year old children showed bilingual advantages on cognitive control performance, Morton and Harper (2007) could not replicate these results in a similar sample using exactly the same methodology. Similar replication problems were observed in adult studies (Costa et al., 2008) and this has led to a questioning of the theoretical foundations for bilingual advantages in controlled processing (Paap & Greenberg, 2013). Morton & Harper (2007) proposed that confounding variables such as socioeconomic status or migration background might overrule the impact of bilingualism in explaining variability on measures of cognitive control.

Which cognitive control component is affected by bilingualism?

All studies that found a bilingual advantage on cognitive control processing reported a main effect of language group with faster overall response times for bilinguals than for monolingual controls (Bialystok et al., 2005b; Martin-Rhee & Bialystok, 2008). This means that congruent (or non-conflict) and incongruent (or conflict) trials are similarly affected by bilingualism in children. This advantage has been described as a Bilingual
Executive Processing Advantage (Hilchey & Klein, 2011) and is indicative of an effect on monitoring processes (Costa et al., 2009). These processes are thought to signal the occurrence of conflict and to determine when conflict resolution has to be put in place to successfully execute a specific task.

Childhood bilingualism has been shown to selectively affect interference suppression, but not response inhibition (Martin-Rhee & Bialystok, 2008). Interference suppression can be tested by two types of conflict tasks: stimulus-stimulus (S-S) or stimulus-response (S-R) incompatibility tasks. S-S tasks such as the Stroop task generate a conflict at the level of stimulus identification, whereas conflicts in S-R tasks, such as the Simon task, occur at the level of response selection. Hence, S-S tasks induce stronger behavioural interferences and are subserved by different neural processes (Frühholz, Godde, Finke, & Herrmann 2008). Bilingual advantages on cognitive control in children have only been found by using the Simon task (Bialystok et al., 2005b; Martin-Rhee & Bialystok et al., 2008; Morton & Harper, 2007), but not by using S-S tasks (Carlson & Meltzoff, 2008). Only in one study, both types of tasks have been used in the same population (Poarch & van Hell, 2012).

What type of bilingualism creates advantages in cognitive control?

So far, two studies have compared cognitive control performance in different populations of bilingual children. More specifically, Carlson and Meltzoff (2008) investigated the early bilingualism effect in two groups of six year old bilingual children and age-matched monolingual controls. The bilingual groups were grouped according to their age of acquisition into simultaneous and sequential bilinguals. Simultaneous bilinguals showed advantages on some cognitive control measures, while the two other groups did not differ from each other. The study had a few drawbacks, though. First, the advantages in the simultaneous bilingual group were only found after controlling for a number of background variables because the two bilingual groups were not matched for L2 proficiency or socio-economic variables. Second, no bilingual advantage was found on the ANT, one of the tasks that is most often used to test effects on inhibition and monitoring (Hilchey & Klein, 2011).

A second study compared four groups of children: simultaneous trilinguals, balanced and unbalanced bilinguals and monolinguals (Poarch & van Hell, 2012).
An advantage was found in the trilinguals as compared to the monolinguals in the Simon task. In the Flanker task, this effect was complemented by a difference between trilinguals and unbalanced bilinguals. These results show that the Flanker task might be more sensitive to differences in proficiency levels between groups of bilingual children.

More recently, studies with bilingual young adults have revealed a direct relationship between language control abilities and cognitive control performance (Festman et al., 2010; Linck et al., 2012; Rodriguez-Fornells et al., 2011). The hypothesis has been put forward that individual with good language control skills are also better at tasks that tap controlled cognitive processing (Prior & Gollan, 2011). This effect, however, has never been attested in bilingual children.

What are the neural correlates of bilinguals’ controlled cognitive processing?

The Bilingual Neural Overlap hypothesis states that bilingualism induces functional plasticity in exactly those regions that underlie language control. An important distinction has to be made between involvement of the PFC and the ACC. While additional involvement of the PFC might facilitate cognitive control in bilinguals (Bialystok et al., 2005a; Garbin et al., 2010), the ACC is tuned by bilingualism so that less activity is needed to perform the same task. This hypothesis has not been tested in children.

The present study

This study intends to investigate cognitive control performance in two groups of L2 proficiency matched simultaneous and sequential bilingual children and monolingual controls. Bilingualism-induced behavioural effects on cognitive control were tested in a numeric Stroop task (a S-S task) and a two-colour Simon task (a S-R task). In addition, correlation analyses were carried out to investigate whether the variability within the bilingual population could be explained by differences in language proficiency or language control abilities. The following prediction was made in the previous chapter: only on those language control tasks in which the amount of controlled processing is connected to behavioural facilitation, correlations can be expected with scores on cognitive control. In practice, this means that only forward translation skills would explain
cognitive control variability. The neural correlates of cognitive control performance were only tested in the Simon task.

### 1.1.1 Methods

**Participants.** A total of 54 right-handed children (mean age = 9 years, 5 months, \(SD = 11\) months; 24 males, 30 females) were selected for this study. Handedness was defined using the Edinburgh Handedness Inventory (Oldfield, 1999). Based on their language background and age of second language acquisition, participants were subdivided into 15 monolingual children (6 males, 9 females, mean age = 9 years; 7 months; \(SD = 3\) months), 16 sequential bilingual children (8 males, 8 females; mean age = 9 years; 5 months; \(SD = 15\) months) and 23 simultaneous bilingual children (10 males, 13 females; mean age = 9 years; 5 months; \(SD = 11\) months). More information is given in Part One, chapter 2, section 1.1.1.

**Language proficiency.** Modified versions from several subtests of the Bilingual Aphasia Test (Paradis et al., 1987) were included in this language test battery. These tasks can be subdivided into single-language tasks (L1 & L2), an interference task (L1 & L2) and a translation task, in both directions. More information is given in Part One, Chapter 2, section 1.1.1.

**Simon task.** Participants lay down in an MRI scanner while they did this task. The Simon task (Simon & Rudell, 1967) consists of a series of red and green squares that are presented either on the left or the right side of the screen. The width of the squares was 10% of the width of the screen and their centre was positioned vertically on its centre line and horizontally at 15% and 85% of its width. Participants were orally instructed to respond as quickly and as accurately as possible to the colour of the squares, ignoring their location. In order to make sure that task instructions were well understood, this task was practiced with a short demo of 10 trials. Instructions were given in the child’s preferred language by a Dutch-French bilingual speaker. The match between stimulus colour and response location was counterbalanced across participants. Participants completed 156 trials composed of 81 (51.9%) incongruent and 75 (48.1%) congruent trials. The stimuli were applied with a jittered inter-stimulus interval (ISI) of 2.2±0.56 seconds (maximum ISI=3.18 s, minimum ISI=1.19 s). The total duration was 6 minutes and 30 seconds.
Neural and behavioural correlates of cognitive control

Figure 2.11 Examples of congruent (left), incongruent (middle), and neutral (right) trials of the numeric Stroop task.

Numeric Stroop task. Participants lay down in an MRI scanner while they did this task. The numeric Stroop task consists of sets of two Arabic digits simultaneously shown to the children. Children were instructed to indicate with a button press (left or right) which of the two digits was numerically larger, ignoring their physical size. Participants were orally instructed to respond as quickly as possible. Stimuli were classified into three categories (Kaufmann et al., 2008; see Figure 2.11): (a) congruent (physical and numerical comparison leading to the same response), (b) incongruent (physical and numerical comparison leading to different responses), and (c) neutral (the stimuli differ only in numerical size). Neutral trials were added to increase the statistical power. 8 single digits were used to create the digit pairs: 1, 2, 3, 4, 6, 7, 8 and 9. Distance was manipulated by changing the numeric distance of the digit pairs with two possibilities: distance 1 or distance 5. The digits were presented in white Arial font on a black background with two different sizes: 32 and 58 points. The stimuli were positioned vertically on the centre line and horizontally at 25% and 75% of the width of the screen. Participants completed 130 stimuli, composed of 43 congruent, 43 incongruent, 44 neutral trials. The two numeric distances were equally distributed across the three categories of stimuli. The stimuli were applied with a jittered ISI (2.7± 0.58 s, maximum ISI= 3.76 s, minimum ISI= 1.78 s). At the beginning of each trial a centred white fixation cross on a black background was projected for 300 milliseconds. The total duration of this task was 6 minutes and 30 seconds.

Behavioural data analysis

Congruence-related performance (Simon & Stroop tasks). The individual analysis of congruence effects was composed of two steps. First, the percentage of correct responses was calculated for each individual, for the whole task and for congruent and incongruent (and neutral) trials separately (in the Stroop task, also for each of the two distances). Children
with an accuracy rate below 50% were excluded from further analysis. Second, mean whole-task, congruent and incongruent (and neutral) response times (in the Stroop task, also for each of the two distances) of all correct responses were calculated for each individual. Only correct responses within 2.5 standard deviations of the total individual mean were included.

Group variables. SPSS 17.0 was used for all statistical analyses. Group analyses were conducted based on the output from the subject-by-subject analyses that were carried out at the first level. Two within-subject factors were distinguished. The first factor was congruence with two levels in the Simon task and three levels in the Stroop task. The second factor was distance with two levels in the Stroop task only. One grouping (or independent) variables, containing three levels, was added to the individual mean accuracy scores and response times: language group (levels: monolinguals, simultaneous and sequential bilinguals). In order to establish the normality distribution of the samples, one-sample Kolmogorov-Smirnov tests were conducted on all dependent variables. Based on the p-values of these analyses, parametric (p-value > 0.05) or non-parametric tests (p-value < 0.05) were carried out.

Neuroimaging data analysis (for Simon task only). For MRI parameters and Data analysis: spatial preprocessing, see Part One, chapter 2, section 2.1.

Data analysis: first-level statistical analysis. In the first level analysis, one general linear model was performed for all participants, modelling incongruent and congruent trials. The experimental design was convolved with the canonical hemodynamic response function (HRF) and its time and dispersion derivatives (Calhoun et al., 2004; Hopfinger et al., 2000) to model the event-related activity in a second-order Taylor expansion of the response (Friston et al., 1998; Henson, 2004). The realignment parameters were also included as regressors. The data were high-pass filtered with a cut-off of 1/128 Hz to eliminate low-frequency noise. From this first level, we computed t-images of parameter estimates for the incongruent-minus-congruent contrast (conflict effect) at each voxel for every participant.

Data analysis: second-level statistical analysis. This contrast was defined for each subject, and the resulting images were used in second-level analysis with the mean response times added as a covariate. First, one sample t-
tests were conducted for each of the groups separately. Then, independent samples t-tests were used to trace group differences. Finally, multiple regression analysis was used to find linear relationships between response latencies and neural activity across all participants. Results of these analyses were thresholded at a minimum of 10 contiguous voxels, and p<.001, uncorrected for multiple comparisons. Talairach Client (version 2.4.3) was used for automated labelling of the localization of neural activity (Lancaster et al., 1997; Lancaster et al., 2000).

1.1.2 Results

Language proficiency, see Part One, chapter 2, section 1.1.2.

Behavioural data

Simon task: congruence-related performance. Mean accuracy rates and response times are reported in Table 2.8. Data from 14 monolinguals, 15 sequential bilinguals and 20 simultaneous bilinguals were used for further analysis. Non-parametric Kruskal-Wallis revealed no significant differences, neither for congruent, $H(2) = .30, p > .05$, nor for incongruent trials, $H(2) = 4.14, p > .05$. A mixed-model analysis of variance with individual main response times as input revealed a highly significant main effect of congruence $F(1,46) = 78.13, p < .001$. No other main or interaction effects were found. For a graphical representation of these data, see Figure 2.12.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>CONGRUENT TRIALS</th>
<th>INCONGRUENT TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acc. (%)</td>
<td>RTs (ms.)</td>
</tr>
<tr>
<td>Mono.</td>
<td>95.43 (2.99)</td>
<td>683.59 (143.96)</td>
</tr>
<tr>
<td>Sim. bil.</td>
<td>94.67 (5.39)</td>
<td>641.15 (104.49)</td>
</tr>
<tr>
<td>Seq. bil.</td>
<td>94.58 (2.54)</td>
<td>655.83 (75.79)</td>
</tr>
<tr>
<td>Total</td>
<td>94.86 (3.99)</td>
<td>657.77 (109.18)</td>
</tr>
</tbody>
</table>

Table 2.8 Mean accuracy rates and response times for congruent and incongruent trials of the Simon task according to language group. Standard deviations are given between brackets.

Simon Task: proficiency correlates. Correlation analyses were conducted between the scores on the L2 and translation tests of the language test battery and the response times and accuracy rates on incongruent trials of the Simon task. Table 2.9 reports the correlation scores between four of
these tasks and accuracy and response times on the Simon task. Note that
the only significant correlation was found between scores on a forward
translation task and accuracy on incongruent trials of the Simon tasks.
Curiously, the correlation turned out to be negative: $r(31) = -.46, p < .01$.

<table>
<thead>
<tr>
<th></th>
<th>BW. TR.</th>
<th>FW. TR.</th>
<th>L2 GR. JUDG.</th>
<th>L2 VERB. FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc. inc.</td>
<td>.16</td>
<td>-.46</td>
<td>.25</td>
<td>-.08</td>
</tr>
<tr>
<td>RT inc.</td>
<td>-.06</td>
<td>-.13</td>
<td>.00</td>
<td>-.23</td>
</tr>
</tbody>
</table>

Table 2.9 Pearson correlation coefficients between scores on L2 and translation tasks, and accuracy rates or response times of the Simon task. Highlighted in green are significant correlations at $p < .05$, highlighted in red are non-significant correlations at $p > .05$.

**Stroop task: distance & congruence effects.** Mean response times are reported in Table 2.10. Mixed-model analyses of variance with two within-group factors (congruence and distance) revealed a significant effect of congruence, $F(2,96) = 81.71, p < .001$, and of distance, $F(1,48) = 135.22, p < .001$, but not of group, $F(2,48) = .19, p > .05$. No further interaction effects were found.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>NEUTRAL TRIALS</th>
<th>CONGRUENT TRIALS</th>
<th>INCONGRUENT TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dist 1</td>
<td>Dist 5</td>
<td>Dist 1</td>
</tr>
<tr>
<td>Monolinguals</td>
<td>1016.66 (236.55)</td>
<td>910.32 (197.28)</td>
<td>965.67 (215.47)</td>
</tr>
<tr>
<td>Sequential bilinguals</td>
<td>1033.53 (173.43)</td>
<td>937.21 (162.33)</td>
<td>955.54 (189.53)</td>
</tr>
<tr>
<td>Simultaneous bilinguals</td>
<td>990.64 (186.12)</td>
<td>900.68 (208.68)</td>
<td>923.73 (174.15)</td>
</tr>
</tbody>
</table>

Table 2.10 Mean accuracy response times for neutral, congruent and incongruent trials with numeric distances one and five of the Stroop task according to language group. Standard deviations are given between brackets.

**Stroop Task: proficiency correlates.** Correlation analyses were conducted between the scores on the L2 and translation tests of the language test battery and the response times and accuracy rates on incongruent trials of the Stroop task. None of the language tasks appeared to be correlated to performance on the Stroop task.
Neuroimaging data

**Within-group analyses: congruence-related performance.** The incongruent-to-congruent contrast images of the Simon task were used for conducting one sample t-tests in the three language groups. A one sample t-test of the incongruent-minus-congruent contrast in monolinguals doing the Simon task resulted in activity in the right dorsolateral PFC (BA 9) and the right insula (BA 13). The same analysis in sequential bilinguals revealed activity in the following regions: the bilateral SMA (BA 6), the middle frontal gyrus (BA 6), the right precentral gyrus (BA 4) and the right superior temporal cortex (BA 22). Simultaneous bilinguals activated the following regions on incongruent trials of the Simon task: the right precentral gyrus (BA 6), the medial frontal gyrus (BA 32) and the bilateral thalami. For each of these activated regions, Table 2.11 reports the Talairach coordinates, T-values and cluster sizes.
Between-group analysis: congruence-related performance. A one-way analysis of variance was conducted to compare the neural activity between the three language groups. A main effect of language group was found in the left posterior cingulate gyrus (BA 23). The F-value and the cluster size of this locus of activity is reported in table 2.12.

### Table 2.11
Results of one-sample t-tests on incongruent-to-congruent contrast images of the Simon task in monolinguals, sequential bilinguals and simultaneous bilinguals. BA = Brodmann area.

<table>
<thead>
<tr>
<th>Activated region</th>
<th>BA</th>
<th>Talairach Coordinates</th>
<th>T-value</th>
<th>Cluster size</th>
</tr>
</thead>
<tbody>
<tr>
<td>R dlPFC</td>
<td>9</td>
<td>53, 6, 33</td>
<td>5.85</td>
<td>33</td>
</tr>
<tr>
<td>R Insula</td>
<td>13</td>
<td>55, -38, 24</td>
<td>4.56</td>
<td>14</td>
</tr>
</tbody>
</table>

### Table 2.12
Results of a one-way analysis of variance on incongruent-to-congruent contrast images of the Simon task. BA = Brodmann area.

<table>
<thead>
<tr>
<th>Activated region</th>
<th>BA</th>
<th>Talairach coordinates</th>
<th>F-value</th>
<th>Cluster size</th>
</tr>
</thead>
<tbody>
<tr>
<td>L Post. cing. gyrus</td>
<td>23</td>
<td>0, -30, 27</td>
<td>10.58</td>
<td>99</td>
</tr>
</tbody>
</table>

### 1.1.3 Discussion

This study investigated the behavioural and neural correlates of bilingual advantages in cognitive control processing in two groups of L2 proficiency-matched simultaneous and sequential bilingual children, and one group of monolingual controls. Two measures of cognitive control were included: a S-S and S-R task. In addition, correlation analyses were carried out to
assess the link between single- and mixed-language proficiency and controlled cognitive processing performance.

Which cognitive control component is affected by bilingualism?

The most important conclusion of this study is that no differences could be detected on two measures of cognitive control between simultaneous and sequential bilingual children, and between these groups and age-matched monolingual controls. The results show that bilingualism has no positive effect on incongruent trials, as would have been predicted by the BICA, or on overall performance, as would have been predicted by the BEPA (Hilchey & Klein, 2011). These results are in line with one previous study that found a similar null effect comparing bilingual children to monolingual controls (Morton & Harper, 2007). However, these results are dissimilar from two other studies that reported an effect on monitoring in bilingual children (Bialystok et al., 2005b; Martin-Rhee & Bialystok, 2008). One reason for this might be that the socioeconomic and migration background of the participants to this study was carefully controlled for in the present study. Morton & Harper (2007) proposed that these confounding variables might overrule the impact of bilingualism in explaining variability on measures of cognitive control.

What type of bilingualism creates advantages in cognitive control?

The early bilingualism effect was tested by recruiting two groups of bilingual children based on their different onset ages of second language acquisition. No differences were seen between these two groups on two measures of cognitive control, neither on incongruent trials, nor on overall performance. This finding is in line with Carlson & Meltzoff (2008), who found no differences on the ANT between simultaneous and sequential bilingual children. Previous studies in young adults, however, have reported an early bilingualism effect in young adults (Luk et al., 2011b). One reason for this might be that L2 proficiency was not matched in these two groups.

In bilingual participants, a link was found between language and cognitive control abilities. This confirmed the observation in previous studies of a connection between language switching and cognitive control (Linck et al., 2012; Prior & Gollan, 2011). The present study was the first to correlate
language translation skills to behavioural scores on a general-purpose conflict task. Specifically, a linear relation was found between accuracy rates on incongruent trials of the Simon task and scores on a forward translation task. Surprisingly, this relationship turned out to be negative: children who scored better on translating words from L1 to L2 had lower accuracy on conflict trials of the Simon task. Similar negative relationships can be found in the literature. In a study with trilingual young adults, Linck et al. (2012) reported that better inhibitory control as measured by the Simon task was associated to larger instead of smaller costs when switching from L1 into L2. However, this effect was non-significant and the same study showed that inhibitory control was most often connected to smaller rather than higher switching costs.

What are the neural correlates of bilinguals’ controlled cognitive processing?

In all three groups, incongruent trials of the Simon task activated an anterior-posterior neural network mostly lateralized to the right hemisphere involving the frontal and temporal gyri, the thalamus and the insula. In contrast to both groups of bilinguals, neural activity in monolinguals was restricted to two clusters in the right hemisphere: the dorsolateral PFC and the insula. Simultaneous bilinguals showed activity in the bilateral task-specific frontal gyri and the superior temporal gyrus. In addition to activity in the frontal gyri, the sequential bilinguals were the only group to show activity in the bilateral thalami. Interestingly, a main effect of language background was found in the left posterior cingulate gyrus (Frühholz et al., 2010). Many of these active regions, such as the precentral gyri and the SMA, can be related to task-specific motor processing demands (Roland, Larsen, Lassen, & Skinhøj, 1980; Halsband, Matsuzaka, & Tanji, 1994). The dorsolateral PFC, one of the regions specifically activated in monolingual children, has been reported as an important brain region for the processing of different types of control tasks (e.g., Braver et al., 2001). The insula and the basal ganglia, including the thalamus, have been linked to activity during conflict tasks (e.g., Frühholz et al., 2010). The posterior part of the cingulated gyrus has been connected to stimulus-response conflicts such as the Simon task (Frühholz et al., 2010).

The combination of an effect of language background at the neural level and a null effect at the behavioural level may seem surprising at face value.
However, the main neural effect reported in this study is located in a region that is no part of the neural language control network (Abutalebi & Green, 2007). It can be suggested that behavioural effects of language processing will only manifest themselves in tasks that recruit regions showing overlap between language and cognitive control.

1.2 T2

Participants to the longitudinal study were invited to be examined again at T2, two years after T1. The same two measures of cognitive control, i.e., the Simon task and the numeric Stroop task, were complemented by an Attention Network Test. Because language control abilities turned out to be a good predictor of cognitive control skills, the participants were regrouped according to their mixing costs on a two-language verbal fluency task.

Which component of cognitive control is affected?

In addition to the two-colour Simon task and the numeric Stroop task, all participants performed an Attention Network Test. The use of the Flanker task (Eriksen & Eriksen, 1974), embedded in an Attention Network Test as the ‘executive control’ component (Fan et al., 2002), is one of the three approaches to test bilingual advantages in cognitive control. The attention network is composed of three components that are subserved by different neural systems (Posner & Petersen, 1990). The first two components of the network, alerting and orienting, are part of a posterior attentional network. The third one, executive functioning, is supposed to be embedded in an anterior attentional network, including the PFC and ACC.

Logically, bilingual advantages would manifest themselves most prominently on the ‘executive functioning’ of the ANT. Costa et al. (2008) confirmed this pattern by showing effects on inhibition and monitoring in the ANT by Spanish-Catalan bilingual young adults. However, a study that used exactly the same task in two groups of bilingual children and a group of monolingual controls could not trace any between-group differences (Carlson & Meltzoff, 2008). Costa et al. (2009) argued that the specific sociolinguistic environment of Catalunya might explain why bilingual advantages are reliably observed in that context.
Is the ‘executive functioning’ component the only part of the attention network to be affected by bilingualism? In addition to the bilingual advantages on incongruent Flanker trials and on overall performance, Costa et al. (2008) unexpectedly found an interaction between alerting and language group, revealing that bilinguals benefited more from the presence of an alerting cue. The orienting network, on the other hand, did not turn out to be influenced by language background. The alerting advantage was explained as a side-effect from the BICA. Indeed, the magnitude of the alerting effect turned out to correlate negatively with the conflict effect.

It should be reminded that all studies that showed bilingual advantages in children found an effect on overall performance but not on inhibition (Bialystok et al., 2005b; Martin-Rhee & Bialystok, 2008). The term ‘overall performance’ is rather misleading because executive processing (or cognitive control) as a whole is not affected. Actually, only incongruent trials are assumed to tap controlled cognitive processing. This means that another type of controlled cognitive processing underlies the perceived effect on overall performance. Costa et al. (2008) proposed monitoring as the relevant factor. Monitoring can be described as a set of processes that keeps track of the probability of upcoming conflict (Verguts & Notebaert, 2008). These processes are most relevant on trials with a different congruence than the previous trial. Bilinguals showed significantly lower switch costs on incongruent to congruent switch trials than monolinguals. This is indicative of a bilingual congruence switching (or monitoring) advantage.

What type of bilingualism creates advantages in cognitive control?

The analyses at T1 had revealed that the age of L2 acquisition was not a good predictor of cognitive control performance in bilinguals. Instead, translation abilities were much more relevant for explaining variability in controlled processing. More specifically, scores on a forward translation task were associated with lower accuracy on conflict trials of the Simon task. In this study, we alluded to the question whether two groups of bilingual children with different language control abilities would score differently on a cognitive control task (compare Festman et al., 2010; Prior & Gollan, 2011; Rodriguez-Fornells et al., 2011). Therefore, all bilingual participants to this experiment were regrouped according to their mixing
costs on a two-language verbal fluency task and compared to the monolingual controls.

**Present study**

The present study intends to investigate the development of cognitive control performance in two groups of L2 proficiency-matched bilingual children and monolingual controls, two years after T1. Bilingualism-induced behavioural effects on cognitive control were tested in a numeric Stroop task (a S-S task), a two-colour Simon task (a S-R task) and a Flanker task (a S-S task), embedded in an Attention Network Test. Overall, congruence-related and switch-related performance analyses were carried out to investigate effects on inhibition, monitoring and congruence switching. All participants were regrouped according to language control abilities. It was expected that language control would be a better predictor of bilingual performance on a cognitive control task than age of acquisition.

### 1.2.1 Methods

**Participants.** Out of the 54 participants that were recruited at T1, a total of 40 children (mean age = 11 years; 4 months, SD = 11 months; 19 males, 21 females) returned for participation at T2. This sample was composed of 11 monolingual children (4 males, 7 females, mean age = 11 years; 3 months; SD = 11 months), 14 sequential bilingual children (7 males, 7 females; mean age: 11 years; 4 months; SD = 1 year; 1 month) and 15 simultaneous bilingual children (8 males, 7 females; mean age = 11 years; 5 months; SD = 11 months). More information can be found in Part One, chapter 2, section 1.2.1.

**Single- and mixed-language verbal fluency.** A detailed description of this task can be found in Part One, chapter 2, section 1.2.1.

**Simon Task.** A detailed description of this task can be found in section 1.1.1.

**Numeric Stroop task.** A detailed description of this task can be found in section 1.1.1 Methods.

**Attention Network Test.** The short version of the ANT was downloaded from Jim Fan’s personal website (http://www.sacklerinstitute.org/users/jin.fan/) and installed on Eprime 2.0. The test was administered on a Dell
Latitude E6500. All participants sat comfortably on a chair in a dimly-lit and quiet room while they did the test. Instructions were given in the child’s preferred language by a Dutch-French bilingual speaker. The short version of the ANT is composed of one demo block of 6 trials, one practice block of 12 trials and three experimental blocks with 48 trials each. All trials contain a central arrow which is surrounded by four surrounding arrows or flankers. Congruence is manipulated by changing the direction of the flankers according to the two following possibilities: the flankers pointing in the same direction of the central arrow (congruent) or in the other direction (incongruent). Alerting is manipulated by changing the location of the cue with the three following possibilities: in the centre of the screen, on the left or right side (spatial) or no cue. Using a 3x2 factorial design, 6 trial types could be distinguished, each of which was equally distributed: 24 congruent with central cue, 24 congruent with spatial cue, etc.

**Behavioural Data Analysis**

**Mixed-language cost.** For a description of this data analysis method, see Part One, chapter 2, section 1.2.1.

**Two-means cluster analysis** was carried out using SPSS 17.0 to partition the scores on the mixed-language verbal fluency into two similar clusters in which each observation belongs to the cluster with the nearest mean: high-proficient language mixers (mean score = 10.10, $SD =$ 0.43) and low-proficient language mixers (mean score = 6.93, $SD =$ 0.39).

**Congruence-related performance (Simon task, numeric Stroop task and ANT).** For a detailed description, see section 1.1.1.

**Switch-related performance (Simon task only).** This analysis was similar to that of congruence-related performance apart from the fact that not congruence but congruence switching determined what category a trial was assigned to. Switching was defined by comparing the congruence of the current trial to that of the preceding one. Depending on whether these two were identical or not, a trial was labeled as a repeat or a switch trial. The output of this data processing stage were mean accuracy scores and response times for both repeat and switch trials.
Group variables. SPSS 17.0 was used for all statistical analyses. Group analyses were conducted based on the output from the subject-by-subject analyses that were carried out at the first level. Three within-subject factors were distinguished. The first factor was congruence with two levels in the Simon task and the ANT and three levels in the Stroop task. The second factor was distance with two levels in the Stroop task only. The third factor was cue location with two levels in the ANT only. One grouping (or independent) variables, containing three levels, was added to the individual mean accuracy scores and response times: language group (levels: monolinguals, simultaneous and sequential bilinguals). In a subsequent analysis, the bilinguals were regrouped into two groups according to their performance on the mixed-language verbal fluency task. This created a third grouping variable with three levels: high-proficient language mixers, low-proficient language mixers and monolingual controls. In order to establish the normality distribution of the samples, one-sample Kolmogorov-Smirnov tests were conducted on all dependent variables. Based on the p-values of these analyses, parametric (p-value > 0.05) or non-parametric tests (p-value < 0.05) were carried out.

1.2.2 Results

Single- and mixed-language proficiency, see Part One, chapter 2, section 1.2.2.

Simon Task: congruence-related performance. Mean accuracy rates and response times on congruence-related performance on the Simon task are reported in Table 2.13. A mixed-model analysis of variance with the individual accuracy scores as input was used to assess within-group effects of congruence and between-group effects of language group. Only congruence reached significance, $F(1,37) = 4.07, p < .05$, with higher accuracy for congruent than for incongruent trials. The accuracy rates of the three groups were equal. A similar analysis was conducted with the individual mean response times as input. Analogous to the accuracy analyses, a highly significant effect of congruence was observed, $F(1,37) = 27.74, p < .001$, with faster responses on congruent than on incongruent trials. No further main or interaction effects were found.
Table 2.13 Mean accuracy rates and response times on congruent and incongruent trials of the Simon task according to language group (first 3 rows) and mixing proficiency (rows 4 & 5). Standard deviations are given between brackets.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>CONGRUENT TRIALS</th>
<th>INCONGRUENT TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acc (%)</td>
<td>RTs (ms.)</td>
</tr>
<tr>
<td>Monolinguals</td>
<td>98.42 (1.67)</td>
<td>571.62 (88.68)</td>
</tr>
<tr>
<td>Sim. bil.</td>
<td>97.17 (2.62)</td>
<td>566.91 (110.11)</td>
</tr>
<tr>
<td>Seq. bil.</td>
<td>97.44 (3.50)</td>
<td>585.84 (74.20)</td>
</tr>
<tr>
<td>L-pr. l. mix.</td>
<td>97.33 (3.57)</td>
<td>521.44 (64.07)</td>
</tr>
<tr>
<td>H-pr. l. mix.</td>
<td>97.14 (2.71)</td>
<td>622.26 (86.92)</td>
</tr>
<tr>
<td>Total</td>
<td>97.60 (2.72)</td>
<td>574.36 (91.88)</td>
</tr>
</tbody>
</table>

Mean individual response times served as input for conducting a mixed-model analysis of variance with ‘mixing proficiency’ as a between-subjects factor with three levels: monolinguals, low-proficient language mixers, and high-proficient language mixers. Table 2.13 reports mean response times for these two new groups. Apart from the highly significant main effect of congruence, a between-subject effect of mixing proficiency was detected, $F(2,37) = 4.83, p = .01$. Bonferroni-corrected post-hoc analyses revealed that this effect was only seen between the two bilingual groups, $p = .01$, with slower response latencies for the high-proficient than for the low-proficient mixers. No significance ($p > .05$) was reached in pairwise comparisons between the monolinguals and the two other groups. The same analysis with mean accuracy scores as input only revealed a main effect of congruence. No interaction effects with congruence were detected.

**Simon task: switch-related performance.** Mean accuracy rates and response times on switch-related performance on the Simon task are reported in Table 2.14. Mean response times served as input for conducting a mixed-model analysis of variance with one within-subjects variable (switch) and one grouping variable (with three levels: monolinguals, high-proficient and low-proficient language mixers). Highly significant main effects of switch, $F(1,37) = 168.19, p < .001$, and language group, $F(2,37) = 4.84, p = .01$, were found. Bonferroni-corrected post-hoc analyses confined this latter effect to differences between the two bilingual groups ($p < .01$), with faster responses for the l-pr. l. mix. than for the h-pr. l. mix.. In addition, a marginally significant interaction effect between Switch and Group was detected [$F(2,37) = 2.83, p = .06$] (see Figure 2.14). No significant main or interaction effects were detected on the accuracy rates.
Table 2.14. Mean accuracy rates and response times on repeat and switch trials of the Simon task according to mixing proficiency. Standard deviations are reported between brackets.

Simon Task: proficiency correlates. Correlation analyses were conducted to assess the relationship between the bilinguals’ mixed-language cost and bilingual performance on the Simon task. Mixed-language costs were significantly and negatively correlated with response times on incongruent trials of the Simon task, $r(27) = -.40, p < .05$ (see Figure 2.13), but not with response times on the congruent trials, $r(27) = -.37, p > .05$. A similar pattern was detected for congruence switching with a negative significant correlation between mixed-language costs and response times on switch trials of the Simon task $r(27) = -.43, p < .05$, but not between these costs and response times on repeat trials $r(27) = -.34, p > .05$. The raw scores on the switching condition were neither correlated to the incongruent, $r(27) = .33, p > .05$, nor to the congruent response times in the Simon task, $r(27) = .37, p > .05$.

Numeric Stroop task: congruence & distance effects. Mean response times on the numeric Stroop task are reported in Table 2.15. A mixed-model analysis of variance was carried out on the mean response times with distance and congruence as within-subject variables and the groups (with three levels: monolinguals, sequential bilinguals and simultaneous bilinguals) as between-subjects factor. In line with the findings from the previous run, highly significant main effects of distance, $F(1,37) = 153.36, p < .001$, and of congruence, $F(2,74) = 64.65, p < .001$, were found. Unlike the previous run, these main effects were complemented by a highly significant interaction effect between distance and congruence, $F(2,74) = 7.76, p = .001$. No further main or interaction effects were found.
Figure 2.13 Scatter plot of the correlation between two- or mixed-language costs and mean response times on incongruent trials of the Simon task. The correlation coefficient is indicated.

Table 2.15 Mean response times on all trial types of the Stroop task according to language group. Standard deviations are given between brackets.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>NEUTRAL</th>
<th>CONGRUENT</th>
<th>INCONGRUENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dist 1</td>
<td>Dist 5</td>
<td>Dist 1</td>
</tr>
<tr>
<td>Mono.</td>
<td>816.63 (153.75)</td>
<td>722.68 (119.19)</td>
<td>792.48 (156.44)</td>
</tr>
<tr>
<td>Seq. bil.</td>
<td>902.61 (103.77)</td>
<td>799.39 (115.73)</td>
<td>830.34 (112.69)</td>
</tr>
<tr>
<td>Sim. bil.</td>
<td>819.30 (160.89)</td>
<td>731.96 (156.44)</td>
<td>758.22 (161.33)</td>
</tr>
</tbody>
</table>

Attention Network Test: congruence and alerting effects. Mean response times on the ANT are reported in Table 2.16. A mixed-model analysis of variance was conducted on the individual mean response times with group as between-subjects factor (with three levels: monolinguals, simultaneous and sequential bilinguals), and cue location (three levels) and congruence (two levels) as within-subject variables. Highly significant main effects of
congruence, \(F(1,37) = 209.45, p < .001\), and cue location, \(F(2,74) = 125.15, p < .001\), were found in addition to an interaction effect between these two variables, \(F(2,74) = 14.86, p < .001\). The group variable turned out to be only marginally significant in interaction with congruence, \(F(2,37) = 2.73, p = .08\).

<table>
<thead>
<tr>
<th>GROUP</th>
<th>CONGRUENT Center</th>
<th>Spatial</th>
<th>No cue</th>
<th>INCONGRUENT Center</th>
<th>Spatial</th>
<th>No cue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono.</td>
<td>634.20 (79.52)</td>
<td>566.42 (100.71)</td>
<td>671.75 (83.34)</td>
<td>774.08 (98.53)</td>
<td>665.24 (133.77)</td>
<td>768.96 (94.89)</td>
</tr>
<tr>
<td>Sim. bil.</td>
<td>610.07 (86.68)</td>
<td>565.00 (93.03)</td>
<td>655.14 (96.97)</td>
<td>735.17 (97.03)</td>
<td>658.64 (115.44)</td>
<td>744.09 (122.58)</td>
</tr>
<tr>
<td>Seq. bil.</td>
<td>612.91 (71.87)</td>
<td>584.56 (84.72)</td>
<td>664.24 (80.81)</td>
<td>783.05 (118.09)</td>
<td>722.39 (118.77)</td>
<td>794.58 (110.39)</td>
</tr>
<tr>
<td>Total</td>
<td>617.70 (78.41)</td>
<td>572.24 (90.47)</td>
<td>662.89 (85.90)</td>
<td>762.63 (104.85)</td>
<td>682.77 (116.96)</td>
<td>768.60 (110.63)</td>
</tr>
</tbody>
</table>

Table 2.16 Mean response times on all trial types of the Attention Network Test according to language group. Standard deviations are reported between brackets.

1.2.3 Discussion

Which cognitive control component is affected by bilingualism?

The results obtained at T1 were replicated two years later at T2 of the longitudinal study with bilingual children: no evidence of a bilingual advantage on inhibitory control (BICA) or on monitoring (BEPA) was found in the Simon and Stroop tasks. Only on the ANT, a non-significant trend could be seen that disfavoured the sequential bilinguals compared to the other two groups. It should be noted that exactly the same null effect was reported by Carlson & Meltzoff (2008) in an ANT study comparing two groups of bilingual children and age-matched monolingual controls.
Figure 2.14 Two line graphs representing mean response times on the Simon task for each language group (x-axis) according to congruence (y-axis, top) or switch (y-axis, bottom). Note the trend towards an effect on congruence switching (below) but not on inhibition (top).
However, after the bilingual population had been regrouped into good and bad language mixers, a language control effect was observed on overall performance. Furthermore, a language control effect on congruence switching was tested by making a distinction between congruence switch and congruence repeat trials. A trend towards an interaction effect between switching-related performance and mixing performance was observed. Importantly, no such difference was seen on congruence-related performance. Monitoring in the form of congruence switching might thus be more affected by language control abilities than inhibitory control (Figure 2.13).

What type of bilingualism creates advantages in cognitive control?

The results of the present study clearly show that the early bilingualism effect is outweighed by the language control effect. Indeed, whereas simultaneous bilinguals, sequential bilinguals and monolinguals showed equal performance on the Simon and Stroop tasks and quasi-equal performance on the ANT, significant differences were found after the bilingual population was regrouped according to mixing proficiency.

Most crucially, the relationship between mixing proficiency and cognitive control performance turned out to be negative. Surprisingly, high-proficient language mixers were outperformed by low-proficient language mixers. This pattern was confirmed by the correlation analyses. Children with a higher mixed-language cost, i.e., who showed the highest performance declines when two-language verbal fluency was contrasted to single-language verbal fluency, were faster on incongruent and on switch trials of the Simon task, exactly those trials that require most controlled processing. The hypothesis has to be put forward that better inhibitors, i.e., those children who were fastest on incongruent trials of the Simon task, inhibit the non-target language to such an extent that language mixing is more effortful than single-language processing. Hence, highly proficient language mixers actually obtain worse than better scores on measures of cognitive control.

1.3 Bilingual development (T2 minus T1)

So far, no longitudinal study has been carried out on cognitive control development in bilinguals. Cross-sectional studies have revealed that
bilingual advantages are most often found in children (but compare Morton & Harper, 2007) and older adults, but not when someone is at the top of his attentional abilities in early adulthood (Bialystok et al., 2005b; Martin-Rhee & Bialystok, 2008). The results at T1 and T2 of this longitudinal study, however, have provided no evidence for any bilingual advantages. If the hypothesis is true that bilingual advantages become attenuated over time, there must be a point in childhood when monolinguals catch up with their bilingual peers. Adding a developmental factor in a longitudinal design would then reveal an interaction between this factor and the language groups, implying developmental differences between the groups.

1.3.1 Methods

The participants of the longitudinal study and the methods used were extensively described in the previous sections of this dissertation. Statistically, analyses of variance were conducted with one between-subjects factor and two (or three) within-subjects factors. The within-subject variables were time (two levels: T1 and T2) and congruence (two levels: congruent and incongruent) for the Simon task, and time, congruence (three levels: neutral, congruent and incongruent) and distance (two levels: 1 and 5) for the Stroop task. Only main effects of time and interaction effects with this factor are reported in this section.

1.3.2 Results

Simon task. Mean differences in response times between T1 and T2 are reported in Table 2.17. Inferential statistics revealed a highly significant main effect of time, $F(1,37) = 83.73, p = .001$, in addition to a significant interaction effect between time and congruence, $F(1,35) = 9.68, p < .01$, and a marginally significant interaction effect between time and group, $F(2,37) = 3.17, p = .05$.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>T2-T1 (CON. TRIALS)</th>
<th>T2-T1 (INC. TRIALS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolinguals</td>
<td>125.31</td>
<td>142.79</td>
</tr>
<tr>
<td>Sequential bilinguals</td>
<td>78.40</td>
<td>94.83</td>
</tr>
<tr>
<td>Simultaneous bilinguals</td>
<td>60.39</td>
<td>77.56</td>
</tr>
</tbody>
</table>

Table 2.17 Differences in mean response times for monolinguals, sequential bilinguals and simultaneous bilinguals between T1 and T2 for congruent and incongruent trials of the Simon task.
**Stroop task.** Mean differences in response times between T1 and T2 are reported in Table 2.18. Inferential statistics revealed a highly significant main effect of time, $F(1,36) = 85.39$, $p < .001$, in addition to a significant interaction effect between time and congruence, $F(2,74) = 7.50$, $p < .01$, and a marginally significant interaction effect between time and group, $F(2,37) = 2.46$, $p = < .10$. No further significant or main effects were found.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>T2-T1 (NEUT. TRIALS)</th>
<th>T2-T1 (CON. TRIALS)</th>
<th>T2-T1 (INC. TRIALS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dist 1</td>
<td>dist 5</td>
<td>dist 1</td>
</tr>
<tr>
<td>Mono.</td>
<td>252.71</td>
<td>214.81</td>
<td>198.07</td>
</tr>
<tr>
<td>Seq. bil.</td>
<td>106.70</td>
<td>109.97</td>
<td>91.02</td>
</tr>
<tr>
<td>Sim. bil.</td>
<td>172.77</td>
<td>166.44</td>
<td>158.02</td>
</tr>
</tbody>
</table>

*Table 2.18 Differences in mean response times for monolinguals, sequential bilinguals and simultaneous bilinguals between T2 and T1 for congruent, incongruent and neutral trials.*

### 1.3.3 Discussion

The results of this developmental study clearly show the added value of using a longitudinal design for investigating cognitive control performance in bilinguals. While no differences were found at each of the two time points of this study, nearly significant differences were found in the developmental patterns of these groups. Even though all children showed behavioural gains on congruent and incongruent trials of the Simon and the Stroop tasks, these developmental differences were more outspoken for the monolinguals than for the two bilingual groups.
Figure 2.15 Line graphs representing mean response times on the congruent and incongruent trials of the Stroop task for monolinguals, sequential bilinguals and simultaneous bilinguals (y-axis) as a function of development (x-axis).
2 Cross-sectional study II

The longitudinal study reported in the previous paragraphs was the first to show that the variability in cognitive control performance of bilingual children can be explained by their language control abilities. Previous studies had already revealed a similar effect in young adults (e.g., Festman et al., 2010). Most studies have argued that good language controllers are good cognitive controllers as well (Festman et al., 2010; Prior & Gollan, 2011). This stands in contrast to the results obtained in bilingual children: proficient language mixers turned out to be disadvantaged on measures of cognitive control.

Which component of cognitive control is affected?

The longitudinal study with bilingual children had shown that overall performance on the Simon task is most reliably affected by bilingualism. It was proposed that congruence switching is the underlying factor that causes an executive processing advantage in bilinguals with good language control abilities. Similar results have been obtained with bilingual young adults. Costa et al. (2008) demonstrated that Catalan-Spanish bilinguals had faster response times than monolinguals on congruent to incongruent switches in a Flanker task. This effect on congruence switching was also accompanied by a bilingual advantage on inhibition. This finding was related to the specific sociolinguistic environment of Catalunya.

What type of bilingualism creates advantages in cognitive control?

The longitudinal study with bilingual children had shown that the effect of the participants’ age of acquisition was outweighed by their language control abilities in explaining cognitive control performance. The critical point in these results was the negative relationship between mixing proficiency and cognitive control performance. Indeed, better language mixers responded more slowly than less proficient mixers. The same relationship was seen between forward translation skills and cognitive control performance. Some previous studies seemed to indicate a similarly negative impact from language control on cognitive control (Rodriguez-Fornells et al., 2011; Linck et al., 2012), yet most studies have argued in favour of a positive relationship between language and domain-general task control (Festman et al., 2010; Linck et al., 2012; Prior & Gollan, 2011).
What could explain this contradiction? Possibly, developmental aspects play a role. Neuroimaging of the prefrontal cortex has revealed that this region is one of the last to mature, in some cases even until the age of 25 (Giedd, 2004). Inhibitory skills are represented in this region. The hypothesis was put forward previously that children who are better inhibitors have the ability to inhibit the non-target language to such an extent that language mixing is more effortful than single-language processing. Hence, highly proficient language mixers are actually worse than better at cognitive control. In adulthood, on the opposite, better inhibition is supposedly not associated with more inhibition being applied to a non-target language or task but with a more efficient recruitment of these processes. As a result, it may be expected that adults with good inhibitory skills in bilingual language processing are also better at cognitive control (Linck et al., 2012; Prior & Gollan, 2011).

What are the neural correlates of bilinguals' controlled cognitive processing?

The Bilingual Neural Overlap hypothesis predicts the specific involvement of language control regions in cognitive control tasks. The left dorsolateral PFC would be activated to a greater extent by bilinguals while the ACC would show less neural activity (Abutalebi et al., 2012; Bialystok et al., 2005a; Garbin et al., 2010). The bilingual effects on neural processing of cognitive control have been well studied; however, the impact of language control abilities on these skills has remained unexplored.

The previous part reported both facilitative and inhibitory behavioural effects of language control on language switching costs and language mixing performance. High-proficient language controllers combined higher activity in controlled processing regions with better behavioural scores on forward switching. The explanation was given that more recruitment of language control regions during L1 to L2 switches might facilitate L2 processing on the subsequent trial. This gives an excellent testing ground for the Neural Overlap hypothesis. If there is overlap between language and cognitive control, high-proficient language switchers might use more neural activity in language control regions for facilitating domain-general cognitive control. In accordance with previous studies, we specifically expected the PFC to be activated to a larger extent by high-proficient language controllers.
The present study

The present study investigates the effects of age of acquisition and language control abilities on the behavioural correlates of the Simon task in two bilingual populations of young adults. Language control abilities were manipulated by regrouping bilingual participants according to performance on a two-language verbal fluency task and by correlating switching costs to response times on the most difficult trials of the Simon task. A main effect of language control, but not of age of acquisition was expected. This effect was expected to be positive.

In addition, the neural correlates of switching-related performance were investigated using fMRI. The hypothesis was tested whether behavioural facilitation on cognitive control would be caused by more recruitment of language control components in high-proficient language switchers. We alluded thus to the question whether advantages on language control tasks transfer to domain-general cognitive control.

2.1 Methods

Participants. A total of 25 Dutch-French right-handed bilingual university students from the Dutch-speaking Vrije Universiteit Brussel in Belgium (mean age = 20.55 years; SD = 1.92 years; 13 males, 12 females) were selected for this study. Based on their onset age of L2 acquisition and self-rated proficiency, participants were divided into two groups: (i) Dutch-dominant simultaneous bilinguals (Sim. Bil.) [onset age of L2 acquisition (oAoA L2) = 0 in L1 and L2 for all 13 participants (7 males, 6 females), mean age = 20.54 years; SD = 0.50 yrs.]; (ii) Dutch-dominant sequential bilinguals (Seq. Bil.) [mean oAoA L2 = 9.25; SD = 0.25 yrs.; 12 participants (6 males, 6 females), mean age = 20.56 years; SD = 0.61 yrs.]. For more information, see Part One, chapter 2, section 2.1.

Single- and mixed-language phonemic verbal fluency and two-language semantic categorization task. For a detailed description of these tasks, see Part One, chapter 2, section 2.1.

Two-colour Simon task. For a detailed description of this task, see section 1.1.1.
For the behavioural data processing on the two mixed-language tasks, i.e., cluster analysis and forward & backward switch costs, see Part One, chapter 2, section 2.1.

For the behavioural data processing on the Simon task, i.e., congruence-related performance and switch-related performance, see section 1.1.1.

For a description of the group variables, see Part One, chapter 2, section 2.1.

For a description of the MRI parameters, the neuroimaging data processing and the data analysis: spatial preprocessing, see Part One, chapter 2, section 2.1.

Data analysis: first-level statistical analysis. In the first level analysis, one general linear model was performed for all participants, modelling congruence repeat (both congruent to congruent and incongruent to incongruent) and congruence switch (both congruent to incongruent and incongruent to congruent) trials. The experimental design was convolved with the canonical hemodynamic response function (HRF) and its time and dispersion derivatives (Calhoun et al., 2004; Hopfinger et al., 2000) to model the event-related activity in a second-order Taylor expansion of the response (Friston et al., 1998; Henson, 2004). The realignment parameters were also included as regressors. The data were high-pass filtered with a cut-off of 1/128 Hz to eliminate low-frequency noise. From this first level, we computed t-images of parameter estimates for the contrast between congruence switch and congruence repeat trials (switching effect) at each voxel for every participant.

Data analysis: second-level statistical analysis. This contrast was defined for each subject, and the resulting images were used in second-level analysis using the mean response times as a covariate. First, one sample t-tests were conducted for the low- and high-proficient language switchers, separately. Then, an independent samples t-test was used to trace group differences. Finally, multiple regression analysis was used to find linear relationships between response latencies and neural activity across all participants. Results of these analyses were thresholded at a minimum of 10 contiguous voxels, and p < .001, uncorrected for multiple comparisons. Talairach Client (version 2.4.3) was used for automated labelling of the localization of neural activity (Lancaster et al., 1997; Lancaster et al., 2000).
2.2 Results

Behavioural results

*Simon task: congruence-related performance.* Mean response times and accuracy rates are reported in Table 2.19. A mixed-model analysis of variance on the response times with congruence as within-subjects variable and age of acquisition (two levels: simultaneous and sequential) and mixing proficiency (two levels: high- and low-proficient) as between-subject variables revealed a highly significant main effect of congruence, $F(1,20) = 9.45, p < .01$. Mixing proficiency was the only between-subjects variable that turned out to significantly predict variance in response times of the Simon task, $F(1,20) = 6.33, p < .05$, with lower response times for the high-proficient language mixers than for the low-proficient language mixers (see Figure 2.16). The contrast between simultaneous and sequential bilinguals did not reach significance, $F(1,20) = .87, p > .05$. No further main or interaction effects were found.

<table>
<thead>
<tr>
<th>L2 AOA</th>
<th>MIX. PRO</th>
<th>CONGRUENT TRIALS</th>
<th>INCONGRUENT TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>RT</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Sim. bil.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>99.24 (1.05)</td>
<td>405.62 (30.60)</td>
<td>99.12 (1.17)</td>
</tr>
<tr>
<td>Low</td>
<td>97.87 (2.42)</td>
<td>447.16 (32.55)</td>
<td>99.01 (1.61)</td>
</tr>
<tr>
<td>Total</td>
<td>98.67 (1.80)</td>
<td>422.93 (36.79)</td>
<td>99.08 (1.30)</td>
</tr>
<tr>
<td>Seq. bil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>98.22 (1.54)</td>
<td>382.20 (67.36)</td>
<td>98.36 (0.72)</td>
</tr>
<tr>
<td>Low</td>
<td>97.78 (2.11)</td>
<td>462.71 (76.80)</td>
<td>96.57 (3.99)</td>
</tr>
<tr>
<td>Total</td>
<td>97.89 (1.92)</td>
<td>442.58 (80.25)</td>
<td>97.02 (3.51)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>98.93 (1.23)</td>
<td>398.60 (41.96)</td>
<td>98.89 (1.08)</td>
</tr>
<tr>
<td>Low</td>
<td>97.81 (2.13)</td>
<td>457.16 (63.37)</td>
<td>97.44 (3.47)</td>
</tr>
<tr>
<td>Grand total</td>
<td>98.28 (1.86)</td>
<td>432.76 (61.87)</td>
<td>98.05 (2.79)</td>
</tr>
</tbody>
</table>

*Table 2.19 Mean accuracy scores and reaction times on the Simon task for all participants divided according to age of acquisition and mixing proficiency. Totals for each independent variable and grand totals are included. Standard deviations are given between brackets.*
Functional and structural plasticity in the bilingual brain

Figure 2.16 Bar graphs comparing main effects of mixing proficiency (above) and of age of second language acquisition (below) on response times for congruent (blue) and incongruent (green) trials of the Simon task. Note the more pronounced differences between high- and low-proficient mixers than between simultaneous and sequential bilinguals. The first difference turned out to reach significance.

Simon task: switch-related performance. Mean response times and accuracy rates for each language group are reported in Table 2.20. Inferential statistics with the same within- and between-subject variables revealed main effects of switch, \(F(1,20) = 60.27, p < .001\), and of mixing proficiency, \(F(1,20) = 6.98, p < .05\), and a marginally significant interaction effect between these two variables, \(F(1,20) = 3.32, p = .08\). No further main or interaction effects were found.

Simon task: proficiency correlates. Correlation analyses were conducted between measures of language control on the two-language verbal fluency task (mixing proficiency) and on the two-language semantic categorization task (backward and forward switching costs) and response times on congruent, incongruent, switch and repeat trials. Table 2.21 reports the Pearson correlation coefficients for all of these correlations. Note that only the correlations between forward switching costs and Simon task performance reached significance, with a different pattern for each trial type (see Figure 2.17).
Neural and behavioural correlates of cognitive control

### Table 2.20
Mean response times and accuracy scores for all participants divided according to age of acquisition and mixing proficiency. Totals for each independent variable and grand totals are included. Standard deviations are indicated between brackets.

<table>
<thead>
<tr>
<th>L2 AOA</th>
<th>MIX. PROF.</th>
<th>REPEAT TRIALS</th>
<th>SWITCH TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>RT</td>
<td>Accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sim. Bil.</td>
<td>High</td>
<td>100.00</td>
<td>395.92(28.09)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>100.00</td>
<td>436.74 (30.39)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>100.00</td>
<td>412.93 (34.76)</td>
</tr>
<tr>
<td>Seq. Bil.</td>
<td>High</td>
<td>98.67</td>
<td>386.47 (62.66)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>99.56</td>
<td>460.12 (76.80)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>99.33</td>
<td>441.71 (81.53)</td>
</tr>
<tr>
<td>Total</td>
<td>High</td>
<td>99.60</td>
<td>393.09 (37.68)</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>99.71</td>
<td>451.77 (67.09)</td>
</tr>
<tr>
<td>Grand total</td>
<td></td>
<td>96.92</td>
<td>427.32 (63.03)</td>
</tr>
</tbody>
</table>

### Table 2.21
Pearson coefficients of correlations between measures of language control (left column) and scores on the Simon task (upper row). Highlighted in red are non-significant correlations (p > .05), in green significant correlations at the .05 level and in bright green at the .01 level.

<table>
<thead>
<tr>
<th>CORRELATIONS</th>
<th>RT CON. TR.</th>
<th>RT INC. TR.</th>
<th>RT REP. TR.</th>
<th>RT SW. TR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing prof.</td>
<td>-.13</td>
<td>-.22</td>
<td>-.13</td>
<td>-.28</td>
</tr>
<tr>
<td>Bw. sw. cost</td>
<td>-.08</td>
<td>-.11</td>
<td>-.06</td>
<td>-.05</td>
</tr>
<tr>
<td>Fw. sw. cost</td>
<td>.51</td>
<td>.59</td>
<td>.52</td>
<td>.58</td>
</tr>
</tbody>
</table>

### Neuroimaging data

**Within-group analyses.** The contrast images of congruence switch versus congruence repeat trials of the Simon task were used for conducting one sample t-tests in the low- and high-proficient language mixers with mean response times as a covariate. One sample t-tests of the switch contrast in high-proficient language mixers doing the Simon task resulted in activity in the left inferior parietal lobule (BA 40). The same analysis in low-proficient language switchers did not reveal any suprathreshold activity. For each of these activated regions, Table 2.22 reports t-values and cluster sizes.
Between-group analyses. The switch contrast images were used for conducting an independent samples t-test between low- and high proficient language switchers with mean response times as a covariate. Additional activity was only found in high proficient language switchers, more specifically in the left dorsolateral PFC (BA 9) (see Figure 2.18). The opposite contrast between low- and high-proficient language switchers did not reveal any suprathreshold activity. For each of these activated regions, Table 2.22 reports t-values and cluster sizes.

Regression analysis. The switch contrast images of all participants were used to perform a regression analysis with the individual mean response times added as a regressor. Slower responding predicted activity in a neural network that was composed of six different regions: two clusters in the right dorsolateral PFC (BA 9), the bilateral ACC (BA 24); the right insula...
(BA 13) and the left inferior parietal lobule (BA 40). For each of these activated regions, Table 2.22 reports t-values and cluster sizes.

<table>
<thead>
<tr>
<th>Activated region</th>
<th>BA</th>
<th>Talairach coordinates</th>
<th>T-value</th>
<th>Cluster size</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIGH PROFICIENT LANGUAGE SWITCHERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L Inferior par. lob.</td>
<td>40</td>
<td>-34, -38, 58</td>
<td>7.32</td>
<td>39</td>
</tr>
<tr>
<td><strong>LOW PROFICIENT LANGUAGE SWITCHERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No suprathreshold activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HIGH&gt;LOW PROFICIENT LANGUAGE SWITCHERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L dl PFC</td>
<td>9</td>
<td>-14, 53, 19</td>
<td>4.29</td>
<td>56</td>
</tr>
<tr>
<td><strong>LOW&gt;HIGH PROFICIENT LANGUAGE SWITCHERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No suprathreshold activity</td>
<td></td>
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</tr>
<tr>
<td><strong>FASTER RESPONDING (all participants)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R dl PFC</td>
<td>9</td>
<td>28, 34, 22</td>
<td>5.09</td>
<td>32</td>
</tr>
<tr>
<td>R Insula</td>
<td>13</td>
<td>32, -1, 18</td>
<td>4.72</td>
<td>25</td>
</tr>
<tr>
<td>L ACC</td>
<td>24</td>
<td>-4, 30, 11</td>
<td>4.41</td>
<td>12</td>
</tr>
<tr>
<td>R ACC</td>
<td>24</td>
<td>12, 29, 6</td>
<td>4.17</td>
<td>11</td>
</tr>
<tr>
<td>R dl PFC</td>
<td>9</td>
<td>38, 23, 38</td>
<td>4.14</td>
<td>12</td>
</tr>
<tr>
<td>L Inferior par. lob.</td>
<td>40</td>
<td>-55, -55, 32</td>
<td>4.05</td>
<td>11</td>
</tr>
<tr>
<td><strong>SLOWER RESPONDING (all participants)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No suprathreshold activity</td>
<td></td>
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</tbody>
</table>

Table 2.22 Results of one-sample t-tests, independent samples t-tests and regression analyses on contrast images of task-switch versus task-repeat trials of the Simon task in low- and high-proficient language switchers. BA = Brodmann area. Highlighted in black are regions that are involved in controlled (language) processing.

2.3 Discussion

This study intended to investigate cognitive control performance in two groups of bilingual young adults with different ages of acquisition. These populations were regrouped according to their language control abilities on a mixed-language verbal fluency task. Besides, the neural correlates of switching-related performance were examined in high- and low-proficient language mixers.

*Which component of cognitive control is affected?*

The analysis of congruence- and switch-related performance showed that language control abilities had a specific effect on monitoring, but not on
inhibition. This was made evident by a trend towards an effect on congruence switching (see Figure 2.19). The same trend was not observed on inhibition. This means that the results obtained in the longitudinal study with children were replicated: bilingualism-related factors have a higher impact on general-purpose monitoring processes than on inhibition.

*What type of bilingualism creates advantages in cognitive control?*

The results of the present study confirm those obtained in the longitudinal study with bilingual children: not age of acquisition, but language control abilities are the relevant factor that explains individual variability in cognitive control performance of bilingual populations. However, an important point of divergence with the longitudinal study needs to be highlighted. Whereas the relationship between language and cognitive control was negative in children, it turned out to be positive in young adults. Indeed, high-proficient language mixers outperformed low-proficient mixers on the Simon task. Moreover, facilitation in forward switching was associated to lower response times on the most effortful trials of the Simon task.

One of the most important conclusions of this study is that the relationship between language and cognitive control in young adults goes in the opposite direction as it goes in children. The results of this study validate the idea that different mechanisms of language inhibition and their effects on cognitive control apply to these two age groups. The hypothesis was put forward that children who are better at inhibition on incongruent trials of the Simon task inhibit their dominant language to such an extent in mixed-language settings that language mixing incurs a higher cost than low-proficient language mixers. In contrast, better inhibition in adults would be associated with a more efficient and more rapid way of using language control to switch to a low-proficient language in a mixed-language context. It should be reminded that the mixed-language semantic categorization task that was used to regroup the young adults in the present study was not administered to the participants in the longitudinal study with bilingual children. Only by doing so and by collecting information about the development of forward switching costs could this hypothesis further be investigated.
What are the neural correlates of bilinguals’ controlled cognitive processing?

Congruence switching in the Simon task is subserved by a neural network that is also involved in language control. A regression analysis on data from all participants showed that slower responding on switch trials of the Simon task was positively correlated with activity in a network including the PFC and ACC of both hemispheres, in addition to the right insula and the left inferior parietal lobule.

It was predicted that facilitation in cognitive control could be explained by more reliance on language control regions for high-proficient language mixers, specifically. This hypothesis was confirmed by within- and between-group analyses of neural activity. High-proficient language mixers turned out to specifically activate the left inferior parietal lobule for switch trials. Moreover, they additionally activated the left dorsolateral PFC as compared to low-proficient language switchers. Interestingly, previous studies have revealed that bilinguals activate the lateral portions of the PFC to a higher extent during general-purpose conflict resolution (Bialystok et al., 2005a; Garbin et al., 2011). This study demonstrates that this effect can also be seen within a bilingual population that is grouped according to language control abilities.

Figure 2.18 Sagittal view on locus of additional neural activity for high-proficient language mixers in the left dorsolateral PFC on the switch trials of the Simon task.
Figure 2.19 Line graphs representing mean response times on the Simon task for congruence-related (top) and switch-related performance (bottom) in function of language group (x-axis). Note the trend towards an effect on congruence switching (below) but not on inhibition (top).
The combination of behavioural facilitation and more controlled processing in high-proficient language mixers forms an interesting parallel between tasks of cognitive and of language control. Negative switching costs on forward switch trials in a mixed-language semantic categorization task were associated to more controlled processing in the bilateral ACC and the left dorsolateral PFC in high-proficient language mixers. Also on the Simon task, this same group of high-proficient language mixers showed more activity in regions subserving controlled processing. The main conclusion of this study is that facilitation in forward switching transfers into domain-general controlled processing.
Chapter 3
General conclusion

This part investigated the neural and behavioural correlates of cognitive control in bilinguals. Three questions were given special attention: ‘Which component of cognitive control is affected by bilingualism?’, ‘What type of bilingualism creates advantages in cognitive control?’ and ‘What are the neural correlates of bilinguals’ controlled cognitive processing?’ The answer to these questions was given from theoretical and empirical perspectives. Table 2.23 gives an overview of the results from both studies that were reported in this part. These results prompt three main conclusions regarding the individual variability of cognitive control skills in bilingual populations.

The first conclusion relates to the developmental aspects of cognitive control in bilingual children. The data reported in this part clearly illustrated the added value of using a longitudinal design. While no differences between simultaneous and sequential bilinguals and monolinguals were found at two separate time points of a longitudinal study, between-group differences were detected in the behavioural changes between these two time points. All children showed huge performance gains between ages nine and eleven, but this progress was more outspoken for monolinguals than for the two bilingual groups. This validates the idea that bilingual advantages in cognitive control manifest themselves most prominently at both extremes of life but that they disappear when the peak of attentional abilities is reached.
<table>
<thead>
<tr>
<th>STUDY</th>
<th>TYPE OF BILINGUAL EFFECT</th>
<th>COGNITIVE CONTROL COMPONENT BEING AFFECTED</th>
<th>NEURAL CORRELATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal study – T1</td>
<td>No bilingual advantage</td>
<td>No effect on inhibition or on monitoring</td>
<td>Main effect in posterior cingulate cortex</td>
</tr>
<tr>
<td></td>
<td>No early bil. effect</td>
<td>Negative correlation between forward translation and inhibitory control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Language control effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal study – T2</td>
<td>No bilingual advantage</td>
<td>No effect on inhibition, monitoring or congruence switching, but a trend towards an effect on inhibition (ANT)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No early bil. effect</td>
<td>Effect on monitoring, trend towards an effect on congruence switching, correlation with inhibitory control and congruence switching</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Language control effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal study – T2 minus T1</td>
<td>Trend towards monoling. advantage</td>
<td>(Nearly significant) effect on monitoring in the Simon task</td>
<td></td>
</tr>
<tr>
<td>Cross-sectional study II</td>
<td>No early bilingualism effect</td>
<td>No effect on inhibition, monitoring or congruence switching</td>
<td>More controlled processing activity in high-prof. l. mixers</td>
</tr>
<tr>
<td></td>
<td>Language control effect</td>
<td>Effect on monitoring, trend towards effect on congruence switching, correlation with inhibitory and congruence switching</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.23 Overview of results from both studies reported in Part Two.
A second main conclusion of this part is that variability in bilinguals’ cognitive control processing cannot be explained by differences in age of acquisition but rather by individual language control abilities. No bilingual advantages or early bilingualism effects were detected on any of the measures of cognitive control being used. However, whenever bilingual groups were grouped according to their language control abilities, a significant language control effect was found. Moreover, different measures of language control such as the mixed-language cost and the forward switch cost were significantly correlated to overall performance on the Simon task, both in children and adults.

Monitoring and not inhibition was pinpointed as the cognitive control component being most affected by language control abilities. Indeed, the traditional analysis of congruence-related performance did not reveal any language control effect on conflict trials. These trials are thought to tap inhibitory control. A different analysis contrasting congruence switch to congruence repeat trials, however, did show a trend towards a language control effect on switch trials. This nearly significant effect was seen both in children and young adults. Switch trials raise monitoring requirements because of the subtle changes to the conflict monitor which keeps track of the probability of upcoming conflict (Verguts & Notebaert, 2008).

A crucial distinction between children and adults was observed in the language control effect. As could be expected, a direct link between language and cognitive control was seen in bilingual young adults. This means that individuals with good language control abilities scored better on the Simon task than those with less well developed controlled processing. In children, the effect was rather the opposite. High-proficient language mixers were disadvantaged instead of advantaged on conflict processing. This pattern was confirmed by correlation analyses. Development-related differences in the effects of inhibitory skills on language control were put forward as an explanation. Whereas improved inhibitory skills lead to more inhibition and more effortful mixed-language processing in children, it is possible that young adults use these skills more efficiently so that they can switch more smoothly between their two languages.

The third conclusion of this part is that the facilitative effects related to language control transfer into domain-general control abilities. The
prediction was made in Part One that only on those measures of language control that showed behavioural facilitation, correlations would be found with cognitive control. This was validated by the data reported in this chapter: only forward switch and mixing costs but not backward switch costs were significantly correlated to aspects of Simon task processing. Moreover, an interesting neural parallel was discovered between language control effects on language switching and domain-general cognitive control. On both instances, high-proficient language mixers combined behavioural facilitation with more controlled processing in neural regions subserving language control.
Part Three
Neurostructural effects of bilingualism
Neurostructural effects of bilingualism

Our brain is not a static organ, but it has the ability to change across the entire lifespan (Pascual-Leone et al., 2011). These changes may be caused by genetic and non-genetic factors. Alzheimer's disease may serve as a good example: this neurodegenerative impairment radically affects neural structure, resulting in massive neuronal death and tissue loss (e.g., Desikan et al., 2009). Even though this pathology can be associated to genetic defects (St George-Hyslop et al., 1987), it has been shown that a non-genetic factor such as bilingualism delays the onset of Alzheimer's disease (Bialystok, Craik, & Friedman, 2007). This finding hints at an interaction between genetic and non-genetic factors and it may be interpreted as evidence that the structural development of the bilingual brain is different from that of the monolingual brain.

The study of structural brain development has not been restricted to clinical populations. Two specific neuroimaging techniques have been used in healthy populations to obtain direct measurements of brain structure: **voxel-based morphometry (VBM)** and **diffusion tensor imaging (DTI)**. VBM is based on whole-brain MRI scans and has mostly been applied to investigate the relative concentration of grey matter (GM) in the brain (Mechelli et al., 2004). DTI is another MRI method; it is generally used to measure different properties of white matter (WM) tracts in the brain. One of the most widely reported DTI measures is fractional anisotropy, which reflects the directional properties of water diffusion processes. This measure is known to depend on the number, size and density of neural connections (Basser, Pajevic, Pierpaoli, Duda, & Aldroubi, 2000; Schmithorst, Wilke, Dardzinski, & Holland, 2005). Therefore, it is often taken as an indirect measure of WM integrity (Luk, Bialystok, Craik, & Grady, 2011a).

Both techniques have generated interesting results in bilingualism research by revealing differences in brain structure between monolinguals and bilinguals. The first VBM study of the bilingual brain was published in the renowned scientific journal *Nature* (Mechelli et al., 2004). The bilingual test group showed increased GM density in the left inferior parietal cortex. The authors of the study concluded that the results could be indicative of a general principle of brain organization: experiential factors do not only alter how our brain functions but they also change the underlying structures. Even one year before this widely cited finding, similar observations were made on WM variability in bilinguals (Coggins III,
Kennedy, & Armstrong, 2004). Much later, this finding has been replicated by using DTI (Luk et al., 2011a). The following paragraphs will discuss the theoretical foundations and empirical bases of experience-induced neurostructural changes, both in GM cortical centers and WM pathways.

Figure 3.1 Graphical representation of neurons and glial cells, the smallest building blocks of neural structure. Source: Allen & Barres (2009, p. 675).
Chapter 1
Theory and literature review

1. Theory

The main goal of this section is to provide the theoretical foundations for bilingualism-induced differences in neural structure. Each of the two following subsections will focus on a different component of the interaction between the structure of the brain (the explained or dependent variable) and the environment (the explaining or independent variable).

1.1 What is neurostructural plasticity?

Neurostructural plasticity is a well-known phenomenon that can be described as the ability of human’s neural structure to overcome limitations of the genome and to adapt to a rapidly changing environment (Pascual-Leone et al., 2005). The time frame required to bring about neurostructural modifications may be remarkably short. Structural plasticity in WM pathways can be observed after only two hours of training (Sagi et al., 2009). Structural plasticity is an intrinsic property across the entire lifespan, even though a gradual age-related decline can be observed (Pascual-Leone et al., 2011).

The most basic entity of neural structure is the neuron or individual nerve cell (see Figure 3.1). The number of neurons and their potential for connections is stunning. Pelvig, Pakkenberg, Stark and Pakkenberg (2008) reported a total number of 21.4 billion neurons in the female and 26.3 billion in the male neocortex, which is the outer (and top) layer of the cerebral cortex. The structures that permit communication between single neurons are called synapses. They are composed of a signal-passing presynaptic neuron, a synaptic cleft and a receiving postsynaptic neuron. In most cases, the presynaptic part is located on the axon of a neuron. This axon is distinct from the soma which contains the nucleus, and the dendrites, on which part the postsynaptic part of the synapse is most often located. The communication between neurons occurs by exchanging either chemicals or neurotransmitters, or electrical currents. Given that there are
5,000 to 10,000 synaptic connections between neurons, the total number of
synapses is approximately 150,000 billion in the neocortex (Tang, Nyengaard, De Groot, & Gundersen, 2001).

Neurons are not the only relevant structures that contribute to synaptic
plasticity. Neurons are surrounded by glial cells (see Figure 3.1). These
cells have receptors that can detect nervous activity through the spillover
of neurotransmitters from the synaptic cleft. Glial cells fulfill different
supportive functions among which the formation of myelin is one of the
most important. Myelin forms a sheath around the neuron that has the
function of increasing the speed of neural communication (Allen & Barres,
2009). The environment of an individual may have a positive or a negative
effect on myelination in the mammalian brain. Young rats that are raised in
an enriched environment show a 33% increase in the number of one type of
glial cells in the visual cortex (Szeligo & Leblond, 1977; Sirevaag &
Greenough, 1987).

More recently, evidence was found for behavioural effects of increased
myelination in professional pianists. Bengtsson et al. (2005) used DTI to
measure anisotropy as an indirect indication of myelination. The
neurostructural effects of piano playing were different depending on when
an individual started piano practice. The number of hours of piano
practicing as a child led to increased myelination in a pathway that carries
sensory motor information for independent finger movement, and in the
corpus callosum, which is of crucial importance for cross-connections
coordinating bimanual movement. In adolescents, a correlation between
piano practicing and myelination was found in the WM bundles that
connect temporal and frontal regions.

A theoretical framework for understanding experience-induced effects on
brain structure is provided by the principles of Hebbian learning. Hebb’s
rule was first proposed in 1949 and states: “Let us assume that the
persistence or repetition of a reverberatory activity (or "trace") tends to
induce lasting cellular changes that add to its stability [...] When an axon of
cell A is near enough to excite a cell B and repeatedly or persistently takes
part in firing it, some growth process or metabolic change takes place in
one or both cells such that A’s efficiency, as one of the cells firing B, is
increased.” (Hebb, 1949, p. 63). This rule thus assumes a link between
neural activity that is generated by external triggers and biological features.
of the single neuron, such as its size (‘growth process’) and structure maintenance (‘metabolism’).

In order to have a better grasp of how external and internal factors might interact to generate structural changes in the brain, a distinction is often made between experience-expectant and experience-dependent types of plasticity (Greenough, Black, & Wallace, 1987). The first type of plasticity is part of normal development, whereas the latter only occurs in specific environments. Each of these two principles of neural plasticity highlights different properties of human brain structure. Experience-dependent neural plasticity can be related to the huge experience-induced individual variability in neural anatomy that underlies different behavioural and cognitive strategies (Kanai & Rees, 2011); experience-expectant plasticity is responsible for the large degree of similarity between individuals of the same species. Kanai & Rees (2011) argue that most attention in neuroscience has been given to the latter type of neural plasticity and its effects on cognition and behaviour. Typically, data are averaged across participants and individual variability is treated as ‘noise’. However, it is exactly this neglected individual variability in behaviour and cognition that can be associated to differences in grey and white matter structures in the brain (Tuch et al., 2005; Johansen-Berg, Della-Maggiore, Behrens, Smith, & Paus, 2007).

Even though individual variability may be caused by neural adaptations to specific environmental pressures, a considerable part of the general architecture of human brains is more or less fixed and homogeneous. An interesting theory that tries to link genetic and experiential factors into one framework of neural functioning and structure is provided by Gerald Edelman’s Neural Darwinism theory (Edelman, 1987). As its name already indicates, this theory is based on the two central tenets of Darwinism: variation and selection. Edelman distinguishes between two types of selection that lead to two different repertoires. The first one is developmental selection which results in a primary repertoire; the second one is called experiential selection and it gives rise to the secondary repertoire (see Figure 3.2).
The term ‘developmental selection’ is reserved for those selective forces that cannot be explained by environmental pressures. This type of selection takes place largely before birth, which explains why even twins with the same genetic footprint are not neuroanatomically identical at birth. The lack of a one-to-one correspondence between genes and neural circuitry underlies one of the general principles of Edelman’s theory that ‘the brain is not a computer’ (Edelman, 1992).

Experiential selection is a second important process: it operates on the already highly variable neural circuitry caused by developmental selection. These selection processes can be compared to Hebbian learning: the strength of some neuronal connections is selectively modified, and others are created as a response to environmental pressure. In order to illustrate the dynamic aspect of this process, Edelman (1987) introduces the idea of ‘re-entrant signaling’. The term re-entrant refers to the notion that new experiences can modify existing maps of interconnected series of neuronal groups and that there is constant feedback and communication between maps that are activated. Edelman compared this process of re-entrant signaling to an orchestra without a conductor that is still playing the symphony on its own. This can only be achieved by a high number of
mutual and simultaneously active connections between all different entities. The metaphor of an orchestra illustrates well the intricate complexity of neuronal communication.

1.2 Enriched environment

One of the external factors that is assumed to have a direct and beneficiary impact on the structure of the brain is an enriched environment. This can be defined as “a combination of complex inanimate and social stimulation” (Rosenzweig, Bennett, Hebert, & Morimoto, 1978, p. 563). Interestingly, these two elements of an enriched environment cannot easily be torn apart. In other words, it is only by the combination of social and inanimate stimulation into one enriched environment that effects on brain functioning will be visible (Ferchmin & Bennett, 1975). First evidence for the effect of environmental stimulation was found in animal studies (Wiesel & Hubel, 1965). Neurobiological researchers had noted that laboratory settings are relatively impoverished compared to the naturalistic wildlife context in which an animal has to survive (Barnea & Nottebohm, 1996). Studies in which laboratory settings were tuned to look more like naturalistic environments, a higher degree of neurostructural plasticity was found (van Praag, Kempermann, & Gage, 2000). The effects of environmental enrichment are not restricted to young organisms, but have also been detected in adult animals (van Praag et al., 2000).

More recently, this evidence for neurostructural effects of enriched environments in animals has been complemented with similar results in humans. Maguire et al. (2000) used VBM to investigate navigation-related neurostructural changes in the brains of taxi drivers in London. GM volumes in the posterior hippocampus, a region known to be critically involved in memory representations, were larger in taxi drivers as compared to a control group. Interestingly, London taxi drivers undergo extensive navigational training, after which a stringent test assesses their active knowledge of all streets and traffic data in London. The representation and storage of this vast mental map thus seems to require additional tissue volume. Moreover, the tissue increases in the posterior hippocampus were complemented by a reverse effect in the anterior parts of the same neural structure with higher tissue volumes in these regions for controls as compared to taxi drivers. The navigational experience thus led
not only to increases in one specific region but also to a reorganization of the neural circuitry in the entirety of that neural structure.

The question was raised whether people with a certain genetically defined hippocampal arrangement are merely predisposed to be employed in a job that requires navigational skills or whether it is the experiential factor itself that explains the differences in brain structure. Correlation analyses turned out to favour the latter explanation. A positive correlation was found between the number of months an individual had been employed as a taxi driver and the GM volumes in the posterior hippocampus.

Another domain often investigated in studies on the effects of experience on neural structure is music. Musicians learn complex motor and auditory skills from childhood and practice these extensively throughout their entire career. The source of stimulations may determine what neural structures are affected. Elbert, Pantev, Wienbruch, Rockstroh, & Taub (1995) demonstrated that professional violinists had larger cortical representation areas for the fingers used in playing the violin than non-musicians. Schneider et al. (2002) reported 130% larger GM volumes in the primary auditory cortex (Heschl’s gyrus) of professional musicians compared to amateur musicians and non-musicians. In addition, these differences appeared to correlate significantly with scores on a musical aptitude test, which taps an individual’s talent for music abilities. This finding might indicate that the morphology of the auditory cortex determines musical talent, rather than the other way around. However, other structural differences in musicians, most notably in Broca’s area, have been shown to correlate with years of musical performance, rather than with musical aptitude (Sluming et al., 2002). It is thus still largely under debate whether early musical training has an impact on brain morphology (nurture) or whether a particular genetically defined neural structure limits the opportunities of musical development (nature).

One way to answer the ‘nature of nurture’ question is by adopting an experimental design, for example by teaching individuals a new skill and by tracking changes in their brain structure before and after this training. Draganski et al. (2004) divided 24 matched adults into two groups. One group received juggling training, and a control group received no training. All participants were scanned at three points in time: before and after the training and three months after the training had ceased. In the
experimental group as compared to the controls, VBM showed an expansion of GM volumes in the bilateral mid-temporal areas and in the left posterior intraparietal sulcus. Interestingly, these structural differences disappeared after the training had ceased.

These results prompt two important conclusions regarding neurostructural training effects. First, structural changes follow functional demands related to the skill that has been trained. Second, this interaction goes in both ways: if the functional demand disappears, the structure will return to its default position.

Bilingualism can be considered another factor that creates an enriched environment that might induce structural plasticity in the human brain. This idea may be referred to as the Bilingual Enriched Environment hypothesis. While the factors that are responsible for structural variability in musicians and taxi drivers are relatively well understood, there is no agreement on the underlying triggers for neurostructural plasticity in the bilingual brain. As a consequence, many studies have found different neural regions to be affected by bilingualism. Two reasons may be put forward for this. First, due to our limited knowledge of the function-structure relationship in the brain, most studies have been exploratory in nature, without making any clear anatomical predictions about the locus of neural differences. Second, there is no theoretical basis for explaining bilingualism-induced differences. If structural changes follow functional demands, an analysis has to be made first on what the specific functions are that make a bilingual brain different from a monolingual brain. While some studies have investigated neurostructural differences in regions that are critically involved in (automatic) linguistic functioning as Broca's and Wernicke's areas (Martensson et al., 2012; Stein et al., 2012), other studies have revealed structural plasticity in regions that only take part in a larger functional network underlying language abilities (Luk et al., 2011a).

More recently, the hypothesis has been put forward that the use of multiple languages would have a major impact on the structure of specifically those regions that are involved in controlled language processing (Abutalebi et al., 2012). This is in line with behavioural and neurofunctional evidence for bilingual advantages in cognitive control processing (see Part Two). In fact, both domain-general and language-specific controlled processing are subserved by similar neural networks (Abutalebi & Green, 2007). It may be
expected that the bilingualism-related effects that are observed in behavioural and functional neuroimaging studies are paralleled by similar effects in neurostructural research.

2. Literature review

2.1 Neurostructural correlates of language abilities

Comparable to the origins of our knowledge about how language abilities are functionally represented in the brain, a first line of evidence for the neurostructural correlates of language skills comes from pathological language development. Studies on dyslexia, a well-known specific reading disability, have revealed a link between this reading impairment and structural symmetry in the planum temporale (Rumsey et al., 1997). This structure in the temporal lobe is a perisylvian language zone in the superior bank of the Sylvian fissure, posterior to the primary auditory cortex. Leftward asymmetry of this structure is a good predictor of left hemispheric language dominance (Geschwind & Levitsky, 1968). More recent studies have found a wide range of neural regions being linked up to dyslexia, including substrates in the frontal, temporal and occipital lobes of the cerebral cortex, in subcortical structures such as the caudate nucleus and the thalamus, and in the cerebellum (Brown et al., 2001; Eckert et al., 2003; Eckert et al., 2005). Without going into detail in this disparate literature, these findings clearly illustrate that structural differences in neural development can be related to functional problems in the domain of language.

Certainly, individual variability in language abilities is not restricted to differences between people with language impairments and healthy individuals. The following paragraphs will discuss two studies that have investigated how neurostructural differences can account for variability in language performance of healthy people. The first one has focussed on the correlates of one specific language skill (vocabulary size, Lee et al., 2007), the second one intended to answer the question whether neurostructural development in early childhood can predict the progression of overall linguistic abilities (Ortiz-Mantilla, Choe, Flax, Grant, & Benasich, 2010; Deniz Can, Richards, & Kuhl, 2013).
Neurostructural correlates of vocabulary knowledge

Neurostructural differences related to vocabulary size form an interesting linguistic parallel to the navigation-related structural changes in the posterior hippocampi of London taxi drivers (Maguire et al., 2000). If a more elaborated mental map of London leads to morphological modifications in regions that underlie spatial functioning, similarly the number of items in the mental lexicon can be expected to correlate with the size of neural structures that are functionally linked to semantic processing.

In a study by Lee et al. (2007), vocabulary knowledge was assessed using a subtest from the Wechsler Intelligence Scale (Wechsler, 1955). Monolingual English-speaking adolescents had to produce the definition of given words. The definitions were rated on a 3-point scale either as an ‘incorrect response’, a ‘poor definition’ or a ‘good definition’. In addition, all participants performed a verbal fluency task in which they were instructed to produce as many words as possible within one minute. This task was added to isolate lexical knowledge from semantic knowledge. VBM analyses revealed significant correlations between semantic knowledge and GM density in the bilateral inferior parietal cortices (supramarginal gyri). Lexical knowledge did not turn out to predict any neurostructural variation.

GM density in the inferior parietal lobule might thus be a neural marker of vocabulary acquisition. The inferior parietal lobule in the left hemisphere is one of the core semantic regions in the human brain, as made evident by functional neuroimaging (Démonet et al., 2005). This finding is a good illustration of the principle that structural changes follow functional demands (see Draganski et al., 2004). People with higher vocabulary skills functionally rely more on regions involved in semantic processing, which leads to structural changes in that specific region.

Does brain structure predict language abilities?

The nature-nurture debate is a controversial issue in neurolinguistics (Mechelli et al., 2004). The main question is whether language experience has an impact on neural structure or whether brain structure might predict language development. Ortiz-Mantilla et al. (2010) dug into this issue using
VBM and reported a link between amygdala volume of normally developing six month old infants and the subsequent development of their preschool linguistic abilities at three different time points. The nuclei amygdalae are situated deep within the medial temporal lobes and are classified as part of the limbic system. The size of the right amygdalae was negatively related to linguistic performance at the ages of two, three and four years. Crucially, this study operationalized the size of a neural structure as a predictor or explaining variable of language performance.

A similar approach was adopted by Deniz Can et al. (2013). Using VBM, they investigated the neural structure of a group of seven month old infants. Five months later, a number of linguistic measures was taken. Correlations between language proficiency and neural structure were found in the following brain zones: the right cerebellum and hippocampus and the left posterior limb of the internal capsule/cerebral peduncle. A differentiation was proposed in the involvement of these different regions, with GM and WM concentrations in the cerebellum being associated with receptive language skills and GM concentrations in the hippocampus with expressive language skills.

Figure 3.3 Correlation between language performance at twelve months of age (right) and GM concentrations in the right posterior cerebellum at seven months (left). Source: Deniz Can et al. (2013, p. 38).
This kind of studies might be of crucial importance for remedying problematic language development in children. Early language performance can be considered as a powerful predictor of later language abilities (National Institute of Child Health and Human Development & Early Child Care Research Network, 2005). However, the study design that was opted for raises a lot of questions. The authors of this study indicate that their research design is longitudinal but they make use of different measures at the two time points of examination: a neurostructural assessment at T1 and a linguistic test at T2. Even though the time gap between these two examinations was only five months, this period is crucial for neural and linguistic development, with an explosion not only in language abilities, but also in intra- and interhemispheric connections (Herschkowitz, 2000). Thus, it cannot be excluded that a combination of developmental and experiential selection processes might have altered the children’s neural structure in the meantime. A longitudinal study of neural structure should therefore track the neurostructural development at every time point. From a more theoretical perspective, the idea that neural structure predicts the development of language skills implicitly assumes that the structure of the brain remains unaltered after the neurostructural assessment has been conducted.

### 2.2 Brain structure and second language acquisition

This section discusses a number of studies that has investigated the interaction between brain structure and second language acquisition. In some of these studies, second language acquisition was used as an explaining variable to understand experience-induced neurostructural changes. In other studies, neural structure was approached from a more static perspective which means that it was used as an explaining variable to predict the speed of second language acquisition.

*Does brain structure predict second language learning success?*

Golestani, Molko, Dehaene, LeBihan and Pallier (2007) tried to attribute the enormous individual variability in non-native speech sound learning to individual differences in the neural structures that underlie the speed of acoustic information processing. It is well known that the distinction between certain acoustically adjacent foreign phonemes is hard to understand, let alone to acquire, when the distinction has no relevance in
the mother tongue, like the /l/-/ɾ/ contrast in Japanese learners of English (Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 2007).

Participants to the study were native speakers of French who were trained to perceive the dental-retroflex contrast in Hindi, a distinction unknown to speakers of European branches of the Indo-European language family. Stimuli were seven items with equal acoustic distance, ranging from the prototypical dental sound to the retroflex prototype. Training sessions took 15 to 20 minutes and were based on the perceptual fading method, which means that once a participant could reliably distinguish between the two prototypes, the distinction between two slightly more similar sounds was practiced, until even the two most similar stimuli could be reliably discriminated. Based on the speed with which they progressed, the participants were grouped into slow and fast learners of the contrast. The fastest learners required the smallest numbers of training blocks to distinguish between the most similar stimuli, whereas the slowest learners could not even discriminate between the two prototypical dental and retroflex sounds after ample training.

A number of neurostructural differences were found between the two groups of fast and slow learners. A first difference concerned the left-hemispheric Heschl’s gyrus within the primary auditory cortex, which is the first cortical processing region of incoming auditory signals. Fast learners had higher WM density and larger GM volumes in this region. They also had a more outspoken leftward asymmetry of WM volumes. Possible causes for these neurostructural differences are greater myelination or a higher number of WM fibres that connect the primary auditory cortex to other regions in charge of analyzing incoming auditory signals. Whatever the reason might be for the observed differences, the higher volumes and density in fast learners might underlie a more efficient processing of phonetic information that requires extremely rapid acoustic discrimination. Earlier clinical studies had already shown a link between below-average leftward asymmetry and poor verbal ability (Rumsey et al., 1997). This study shows that similar neurostructural differences can be seen in a population of people that do not have any language disabilities.

A second difference was found in the inferior parietal lobule. This region is active during phonetic tasks and has been suggested as the location of the phonological store in verbal working memory. The exact same region was
also related to the frequent use and early acquisition of a second language (Mechelli et al., 2004). This makes the authors conclude that there is a certain link between non-native speech learning and more general aspects of second language proficiency.

Despite the similarities between these two studies, their setup is radically different. While the Golestani et al. (2007) study attempts to explain variability in speech sound learning (the dependent variable) by neurostructural differences caused by neurobiological factors unrelated to linguistic development (the independent variable), the Mechelli et al. (2004) study shows the effect of two language-related variables (age of acquisition and proficiency as independent variables) on neural structure (dependent variable). The immense theoretical divide between these two studies can be summarized as follows: if a static, biologically defined factor such as neural structure predicts second language achievement, then how can bilingual development induce structural plasticity in the brain?

There are a few drawbacks regarding the relevance of the study by Golestani et al. (2007) for discussions on the interaction between neural structure, second language acquisition and bilingualism. In contrast to the study by Mechelli et al. (2004), all participants were monolingual speakers, which did not allow for an assessment of the impact of language experience on foreign speech learning or possible interactions between an experiential factor (number of languages spoken) and a biological one (brain structure). In addition, the phonemes were presented in isolation. This means that the most crucial feature of language, which is the communication of meaning, was ignored. Hence, the major difference between the two groups of fast and slow learners was not localized in a language-related zone, but in the primary auditory cortex. The neurostructural differences between the two groups were thus not related to language processing but to auditory processing differences.

Second language learning changes neural structure

The following section discusses two longitudinal studies that operationalized language proficiency as an explaining variable for variation in neural structure. Each of these studies focused on different manners of second language acquisition: Stein et al. (2012) investigated a context
where the learners were immersed into a new language; Mortensson et al. (2012) investigated the effects of intensive linguistic training.

Participants to the first study were a group of American-born exchange students in the German-speaking part of Switzerland (Stein et al., 2012). A combination of linguistic measurements of writing proficiency and neurostructural measurements were recorded at arrival in Switzerland and after five months of immersion in the new linguistic environment. Interestingly, a correlation was found between the progress in second language proficiency and their increase in GM density in Broca’s area. Language-related neural circuitry in the IFG thus shows short-term adaptations to increases in non-native language proficiency. This finding easily fits in with a functional neuroimaging study that reported relatively fast neural convergence in Broca’s area between a native and a late acquired second language. Only after six months, Chinese-born exchange students in the Netherlands activated similar regions for processing Dutch, even though they had never before been exposed to that language (Indefrey et al., 2005).

A second study investigated the brain development in interpreters during a three month intensive linguistic training (Martensson et al., 2012). After training, the interpreters had higher hippocampal volumes and increased cortical thickness in regions that are highly relevant for linguistic processing such as the left IFG (Broca’s area) and middle frontal gyri, and the STG (Wernicke’s area). A further distinction was made between interpreters who acquired the foreign language rapidly and others who struggled with the new learnt language. The first group showed structural plasticity in the right hippocampus and the left STG (Wernicke’s area), whereas the second group displayed larger GM increases in the frontal gyri (among which Broca’s area).

This finding illustrates that structural changes may be different for functional demands related to language reception and production. While fast learners showed increases in posterior brain regions involved in language reception, slow learners had higher volumes of GM in anterior regions that subserve language production. Again, a parallel can be seen between brain function and structure. Functional neuroimaging studies have revealed that low-proficient bilinguals show compensation for their lower proficiency by activating frontal regions more extensively than high-
proficient bilinguals (Vingerhoets et al., 2003). In contrast, high-proficient bilinguals show more activity in posterior regions, such as in the superior temporal and temporoparietal cortices (Dehaene et al., 1997; Perani et al., 1996).

2.3 Neurostructural effects of bilingualism on GM

In contrast to the short-term neural adaptations that underlie foreign language acquisition, this section will have a look at the long-term neurostructural changes caused by bilingualism. The general idea will be that the frequent use of more than one language leads to general changes that make the bilingual brain differ from the monolingual one.

Figure 3.4 Bilingualism-induced structural plasticity in GM density of the left inferior parietal lobule (top) as a function of L2 proficiency (middle) and age of L2 acquisition (bottom).
Mechelli et al. (2004) used VBM to study regional differences in GM concentration between bilinguals and monolinguals. In addition to the grouping variable used to distinguish monolinguals from early and late bilinguals, individual measures of onset age of second language acquisition and second language proficiency were added as regressors to the statistical model. A battery of standardized neuropsychological tests was used which included different levels of linguistic analysis, both at the productive and receptive level. Overall proficiency, as indexed by the first component of a dimension reduction statistical test, was shown to correlate positively with GM density in the left inferior parietal cortex. Overall proficiency correlated negatively with onset age of acquisition. The same negative relationship was seen between GM density and onset age (see Figure 3.4).

The authors of the article interpret this correlation between age of acquisition and neural structure in light of the nature-nurture discussion (Mechelli et al., 2004). Since social experience plays a predominant role in early bilingualism, it cannot be concluded, they argue, that individuals with a particular neural structure are genetically predisposed to acquire a second language. Rather, it can be assumed that the environment triggers the structural change.

What is the reason for the increased GM density in the left inferior parietal lobule? The initial hypothesis suggested verbal fluency as the relevant factor. Previous functional neuroimaging studies had revealed that the supramarginal gyrus takes part in neural circuits underlying verbal fluency (Warburton et al., 1996). However, no further information was given on why functional demands for verbal fluency skills would be different for monolinguals and bilinguals. A later study could hold the key for a better understanding of the bilingualism-induced difference in the structure of that particular area. Lee et al. (2007) used VBM analyses to demonstrate that, at least in monolinguals, vocabulary knowledge and not verbal fluency, correlates with changes in GM density in approximately the same region (coordinates were x = -44, y = -54, z = 46) as in the bilingual study (coordinates were x = -48, y = -59, z = 46).

Thus, the increased vocabulary size required for bilingual functioning seems to be responsible for a structural change. It speaks for itself that...
bilinguals need a more extensive vocabulary than monolinguals. It has been estimated that around 3,000 words form a crucial threshold for learners to fluently use their new language (Nation, 1993). The functional need to store a higher number of lexical items may be related to structural changes in vocabulary-related neural regions.

These neurostructural findings can shed new light on how lexical items are stored in the brain. If vocabulary size in monolinguals correlates with GM density in a region that shows significant differences between mono- and bilinguals, it can be assumed that this particular region stores words from different languages. This is in accordance with the notion of one common store underlying lexical knowledge in all languages of a bilingual individual (see van Heuven & Dijkstra, 2010).

Would the GM volumes in the left inferior parietal lobule correlate to L2 vocabulary knowledge in bilinguals? Mechelli et al. (2004) could not provide the answer to this question because no direct comparison was made between L2 lexical proficiency and GM density. It would even be unsure if this is a valid way of assessing a bilingual's vocabulary size. Many studies have revealed lower scores for simultaneous bilinguals on L2 vocabulary measures than matched monolinguals (Craik & Bialystok, 2006; Fernandes, Craik, Bialystok, & Kreuger, 2007). Even in their stronger language, balanced bilinguals turn out to score at a lower rate than non-balanced bilinguals and monolinguals (Gollan, Fennema-Notestine, Montoya, & Jernigan, 2007). Single-language measures of vocabulary knowledge will thus be insufficient to explain bilingual variation in a vocabulary-related neural region. In other words: if GM density in the left inferior parietal region correlates with (single-language) vocabulary size in monolinguals, it would be illogical to assume that GM increases in bilinguals are associated with a smaller vocabulary size.

An alternative method to rate bilinguals’ vocabulary knowledge is the ‘either-language’ method, which means that bilinguals are credited for producing a correct word in at least one of their languages. It is well-known from language educational theories that there is an important distinction between the development of conversational fluency in a language (Basic Interpersonal Communicative Skills, BICS) and the acquisition of concepts and ideas needed for success in school (Cognitive Academic Language Proficiency, CALP) (Cummins, 2008). If each of these language components
is linked to a different language, the bilingual lexicon might be functionally distributed over both languages. In a single-language test, a bilingual would normally be punished for not knowing the word in the specific testing language, yet it might be that the concept is known in the other untested language. Either-language testing can be implemented by testing vocabulary items first in language A and then in language B. If an item is not known in language A, it may be retested in language B. If it is known in that language, the score is increased accordingly (Muñoz-Sandoval, Cummins, Alvarado, & Ruef, 1998). By using this method, scores end up higher for bilinguals than for monolinguals (Alvarado, 2000) and higher for balanced than for unbalanced bilinguals (Gollan et al., 2007). This parallels the pattern seen in neurostructural studies. The hypothesis is thus put forward that an either-language method is the only way to measure vocabulary size so that it correlates with neurostructural differences in vocabulary-related regions.

**Bilingualism and adaptations in the control network**

Not only overall vocabulary size but also the higher demands on the articulatory repertoire might have an effect on the structural correlates of the bilingual brain (Abutalebi et al., 2013a). In fact, it can be assumed that there is a certain parallel between the extra resources that are required for storing more lexical items and for articulating more phonemes. Abutalebi et al. (2013a) investigated GM density in the left putamen of a multilingual (trilingual) population. The left putamen is part of the basal ganglia, which play an important role in bilingual language processing (Crinion et al., 2006). Increased GM density in the left putamen was detected in multilinguals as compared to monolinguals. Besides, functional neuroimaging revealed that the left putamen was specifically involved in naming pictures in L3, their least proficient language. It might thus be that the larger articulatory load of speaking a less-proficient language leads to structural modifications in specific substrates that underlie these skills.

Structures in the basal ganglia such as the caudate nuclei form only one part of a larger network that might underlie language and cognitive control functions in bilinguals (Abutalebi & Green, 2007). Another part of this network is the dorsal ACC, in the limbic lobe. In a study with mono- and bilingual participants, Abutalebi et al. (2012) used VBM to investigate the relationship between neurofunctional and behavioural performance on a
cognitive control task and changes in ACC GM volumes. A significant correlation was found in bilinguals between the functional conflict effect (contrasting neural activity during incongruent and congruent trials) and ACC structure: higher ACC GM volumes were associated with more neural activity in that region. The correlation was not significant for monolinguals. Furthermore, a significant correlation was found between the behavioural conflict effect (subtracting mean response times on congruent trials from those on incongruent trials) and neurostructural ACC variability. Higher volumes of GM in the ACC were related to faster cognitive conflict processing. Again, this was only observed in bilinguals, but not in monolinguals.

The analysis of the behavioural data with session as a within-group variable with two levels (first and second), provides another interesting perspective on the interaction between neural structure and behavioural adaptations. Even though reaction times were not significantly different between the two groups, the bilinguals as opposed to the monolinguals showed a marked decrease in response times from the first to the second session. Differences in neural structure thus did not lead to overall better performance, but to enhanced ability to adapt to conflict situations. This corresponds to the proposed role of the ACC as a general-purpose conflict monitor that keeps track of conflict probability based on contextual intra- and extra-task factors (Verguts & Notebaert, 2008; Botvinick et al., 2001).

2.4 WM variability in bilinguals

White matter consists of glial cells and myelinated axons. Its function is the transmission of signals between different regions of the cerebrum or between a cerebral region and subcortical centers. The largest WM structure is the corpus callosum (CC), a major commissure or bundle of axons connecting the two cerebral hemispheres. It consists of 200-300 million axons (Abraitiz et al., 1992; Tomasch, 1954). Environmental factors, such as extensive music training, have been shown to affect the structure of the CC (Innocenti & Frost, 1979; Schlaug, 2001; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995). The CC is traditionally divided into an anterior part or a body, and a posterior part called the splenium. A third part is the isthmus: it is markedly thinned and is located between the body and the splenium. Some of these regions have been related to aspects of linguistic processing. Castro-Caldas et al. (1999) found that the posterior part of the
midbody was significantly larger in literate versus illiterate women. The splenium has been reported to carry word information (Funnell, Corballis, & Gazzaniga, 2000). In the same area, Hines, Chiu, McAdams, Bentler and Lipcamon (1992) found a positive correlation with verbal fluency.

The importance of WM pathways in language processing is further highlighted by the disconnection theme in aphasiology (Catani & Mesulam, 2008). Lesions to WM pathways may lead to dysfunctions of higher cognitive abilities (Catani & Hytche, 2005). One example of such a disconnection syndrome is conduction aphasia. In contrast to productive or receptive types of aphasia, this condition is mainly characterized by poor repetition skills with preserved comprehension and speech production (Damasio & Damasio, 1980). The cause of this language loss is a lesion to the fibres between the motor and sensory speech systems in the frontal and temporal lobes, respectively. This group of fibres runs deeply into the WM of the frontal, parietal and temporal regions and is located around the Sylvian fissure. Because of the arching shape of its fibres, it is called the arcuate fasciculus (AF; see Figure 3.5).

![Figure 3.5 Tractography reconstruction of the arcuate fasciculus. Numbers indicate the cortical projections of the segments: 1, sup. temp. l.; 2, middle temp. l.; 3, IFG and precentral g.; 4, middle fr. and PCG; 5, SMG; 6, angular g. Source: Catani & Mesulam (2008, p. 957).](image-url)
Tractography studies based on DTI have revealed a more detailed anatomy than could be expected from clinical findings (Catani, Jones, & Hytche, 2005). First, the direct connections between Broca’s and Wernicke’s areas are accompanied by an indirect pathway passing through the inferior parietal cortex. This pathway runs parallel to the direct route and is composed of two different segments: an anterior segment connecting Broca’s territory with the inferior parietal lobe and a posterior segment connecting the inferior parietal lobe to Wernicke’s territory (see Figure 3.6). Second, the arcuate fibre terminations extend beyond the classically defined areas of Broca and Wernicke. That is the reason why Catani et al. (2005) have proposed to label these arcuate endpoints as Broca’s and Wernicke’s territories instead of regions, thereby recognizing that adjacent regions are involved in higher-level linguistic processing (Matsumoto et al., 2004). These two territories were proposed to be complemented by a third territory in the inferior parietal lobule: the Geschwind territory. This region, at the boundaries of the parietal, temporal and occipital lobes might serve as a locus of convergence for multimodal sensory inputs, allowing for the development of semantic content. It is also exactly the region where bilinguals show higher GM density (Mechelli et al., 2004).
Beside the AF in the region around the Sylvian fissure, a number of other ventral WM pathways in non-perisylvian regions may play additional roles in language processing. These pathways are called the *inferior longitudinal fasciculus*, the *uncinate fasciculus*, and the *inferior fronto-occipital sulcus*. All of these pathways connect medial and inferior temporal and occipital regions involved in semantic processing with traditional language networks in the perisylvian region (Catani & Thiebaut de Schotten, 2008, see Figure 3.6).

The *inferior longitudinal fasciculus* (ILF) connects the temporal with the occipital lobe: it carries visual information by linking object representations to lexical labels (Catani et al., 2003; Mummery et al., 1999). This fibre tract has been shown to play an important role in reading: a progressive and selective degeneration of the ILF may cause pure alexia (Epelbaum et al., 2008). The *inferior fronto-occipital fasciculus* (IFOF) is the only direct connection between the occipital and frontal lobes (Catani, 2007). Little is known about its function. Interestingly, comparisons between the neuroanatomy of monkeys and men have revealed only little similarities in the IFOF (Catani, Howard, Pajevic, & Jones, 2002). This means that this fasciculus might represent a unique prerequisite for species-specific cognitive abilities in humans (Catani, 2006). The *uncinate fasciculus* connects the anterior temporal lobe to the orbitofrontal area, including the IFG (Catani et al., 2002). It may play an important role in linguistic tasks that require connections from temporal to frontal components of the language network, examples of which are: lexical retrieval, semantic associations, and confrontation naming (Grossman et al., 2004; Lu et al., 2002).

Coggins et al. (2004) were the first to investigate WM variability in bilinguals. This study measured the regional-to-total area ratio of five different CC areas: the anterior part, the anterior and posterior parts of the midbody, the isthmus and the splenium. A significant difference between the two groups was found in the anterior midbody with a larger ratio for bilinguals than for monolinguals. This part of the CC is connected to cortical regions that are primarily dedicated to motor functions (De Lacoste, Kirkpatrick, & Ross, 1985; Dimond, Scammell, Brouwers, & Weeks, 1977). These significant differences were related to the higher needs for phonetic capacity in multilingual language processing. The more sounds an
individual has to produce, it was argued, the more need there is for neural structures that underlie mouth and lip adjustments. This conclusion is thus in line with the Bilingual Enriched Environment hypothesis which predicts bilingualism-induced structural plasticity in regions that subserve abilities that bilinguals need to a greater extent than monolinguals.

A recent study has used DTI to compare bilingual and monolingual participants (Cummine & Boliek, 2013). It had a two-fold aim: first, it intended to compare values of fractional anisotropy (FA) in two groups of monolingual and bilingual young adults; second, scores on a naming task were taken as a regressor to explain individual variability in WM integrity (Cummine & Boliek, 2013). Participants were English monolinguals and Chinese-born bilinguals who acquired English after age five. No regions of increased FA values were detected in the bilingual group. However, the regression analysis revealed differences between the groups. Monolinguals showed a negative relationship between naming response times and FA values in the bilateral frontal lobes, the left intraparietal sulcus and left parietal occipital sulcus. Interestingly, bilinguals showed a negative relationship between naming response latencies and FA values in a number of regions including the caudate nucleus and the cingulate cortex, two regions reliably shown to be involved in controlled language processing (Abutalebi & Green, 2007).

2.5 Bilingualism as cognitive reserve

Cognitive reserve refers to the ability of the brain to cope with increasing damage while still functioning adequately (Valenzuela & Sachdev, 2006). Individuals with higher cognitive reserve will perform better than others who have exactly the same structural deterioration. Hence, cognitive reserve is a sort of plasticity that manifests itself by individual differences in the behavioural correlates of structural brain pathology. Empirical evidence for cognitive reserve was first reported in patients with Alzheimer's disease (Katzman et al., 1988). A discrepancy was found between the degree of structural damage due to neurodegeneration and the clinical manifestations of the disease. It was shown that patients with little functional loss had larger brain weights and more neuronal connections than age-matched controls with the same structural damage but more extensive functional losses. It seemed as if these additional neuronal resources created a sort of reserve to compensate for the structural
damage. Cognitive reserve can thus be interpreted as a facilitator of neural plasticity in the face of ongoing damage increases.

One large review study of studies on brain reserve revealed that a number of factors might contribute to protection against dementia: education, high occupational status, high levels of premorbid intelligence, and mentally stimulating leisure activities (Valenzuela & Sachdev, 2006). Among these factors, the engagement in stimulating activities appeared to be the most robust predictor of delayed dementia because the effect remained significant even after controlling for potentially confounding factors as age, education and occupation. If the Bilingual Enriched Environment hypothesis is true, bilingualism might be one of the stimulating activities that contributes to this cognitive reserve.

The effect of lifelong bilingualism on cognitive reserve was assessed in a large-scale Canadian study on 184 elderly patients with dementia (Bialystok et al., 2007). Participants were only classified as bilinguals if they were fluent in their second language and if they had used both languages throughout the majority of their life. In all instances, English was the participants’ second language. The relevant independent variables taken into account were the age of onset of dementia symptoms and the age of the first clinic appointment.

Bialystok et al. (2007) found a significant 4.1 year delay in bilinguals in the onset of symptoms of dementia and a 3.2 year delay in the age of first appointment. Despite the considerable differences in the manifestation of dementia, an objective assessment of the degree of dementia did not show any differences between the two groups. It was concluded then that bilingualism is one instance of a stimulating activity that might result in ‘behavioural brain reserve’ (Valenzuela & Sachdev, 2006), a finding later replicated in a similar study by the same research group (Craik, Bialystok, & Friedman, 2010). The interpretation of these studies is not that bilingualism delays the neurodeterioration associated with ongoing dementia, but that it protects the brain against the functional consequences of this structural damage. Even though the exact mechanisms of behavioural brain reserve are poorly understood, a direct link can be made between cognitive reserve and structural plasticity. The following potential causes are often listed: increased generation of neurons, synapses and
Neurostructural effects of bilingualism

arborized dendrites and functional reorganization of brain networks (Valenzuela & Sachdev, 2006).

Chertkow et al. (2010) attempted to replicate these findings in a more fine-tuned study design composed of different bilingual populations. A first distinction was made between multilinguals and bilinguals. Migration was a confounding variable because all the multilinguals were immigrants to Canada. Within the bilingual population, a further distinction was made between native speakers of English and French. Results showed that multilingualism but not bilingualism delayed the onset of Alzheimer's disease. Within the bilingual group, surprisingly only the French natives showed cognitive reserve.

An interesting finding about the structure-function relationship in bilinguals with Alzheimer's disease was found in a cerebral atrophy study with bilingual patients and monolingual controls matched for cognitive performance (Schweizer, Ware, Fischer, Craik, & Bialystok, 2012). Brain atrophy is a common feature of neurodegenerative diseases: it refers to the loss in the number of neurons and the connections between them. If bilingualism protects against the clinical manifestation of dementia, the degree of atrophy would be higher in bilinguals with a comparable functional loss. This hypothesis was confirmed: in exactly those neural regions that are used to distinguish patients with Alzheimer's disease from healthy controls, computed tomography scans of bilinguals showed increased atrophy as compared to monolingual controls. It was once more confirmed that bilingualism does not affect the pathological causes of Alzheimer's disease but that it alters the functional correlates of structural damage.

One weak point of these studies is that bilingualism and migration status are most often confounded. Most notably, the absence of bilingual effects in English-dominant Canadian-born bilinguals in Quebec (Chertkow et al., 2010) prompts the importance to disentangle migration and bilingualism in research on patients with Alzheimer's disease (Fuller-Thomson, Nuru-Jeter, Richardson, Raza, & Minkler, 2013). In a study with non-immigrant Japanese Americans living in Hawaii, no multilingual effect was found on the rate of cognitive decline (Crane et al., 2010). However, apart from the obvious fact that confounding multilingualism and migration is not an example of good research practice, no theoretical foundation has been
given on why migration would play a role and multilingualism not. Given the finding that a trend of cognitive reserve can also be observed in non-immigrant French-English bilinguals in Quebec, migration can be considered to add up to multilingualism in creating cognitive reserve. Both the experiences of being exposed to different cultures or to different languages meet the criteria of an enriched environment.

The bilingualism-induced cognitive reserve hypothesis has been tested more directly by measuring structural correlates of aging in bilinguals. Aging has been shown to have a direct impact on brain structure with both WM integrity (Madden, Bennett, & Song, 2009) and GM volumes (Fjell & Walhovd, 2010) being adversely affected. The hypothesis goes that cognitive reserve is made possible by protecting WM structures against age-related neurodegeneration (Petrosini et al., 2009). Luk et al. (2011a) used DTI-based FA values to measure WM integrity in bilinguals. If lifelong bilingualism results in cognitive reserve, WM integrity is expected to be higher in older bilinguals as compared to monolinguals. The functional correlates of potential differences were assessed using resting state functional connectivity analysis between GM regions adjacent to relevant WM pathways.

The cognitive reserve was confirmed by the WM and functional connectivity data (Luk et al., 2011a). Higher FA values in bilinguals were observed in the CC extending posteriorly into the bilateral superior longitudinal fasciculi, and anteriorly to the right inferior frontal–occipital fasciculus and uncinate fasciculus. In addition, the functional connectivity analysis revealed different patterns for monolinguals and bilinguals. The seed voxel in the left IFG, an important region involved in language processing and switching (Garbin et al., 2011; Luk et al., 2010) showed stronger functional connectivity in bilinguals with posterior regions including bilateral middle temporal gyri, right inferior parietal lobule, precuneus, bilateral middle occipital gyri, and the left caudate. The monolinguals, in contrast, showed stronger functional connectivity for the left IFG with other anterior areas, including bilateral precentral gyri, right superior frontal gyrus, right middle frontal gyrus, and left medial frontal gyrus. The increased WM integrity in long-range WM pathways such as the IFOF thus appears to be in line with the stronger functional connectivity
between anterior and posterior regions. On the opposite, monolinguals have stronger intrafrontal connectivity.
Chapter 2
Data report

1. Longitudinal study T1

The Bilingual Enriched Environment hypothesis predicts that bilingualism is one of the stimulating activities (Valenzuela & Sachdev, 2006) that may induce performance-enhancing structural changes to the brain. Neurostructural plasticity is a well-known phenomenon that can be described as the ability of humans’ neural structure to overcome limitations of the genome and to adapt to a rapidly changing environment (Pascual-Leone et al., 2011). Bilingualism-induced brain plasticity has been tested in studies using VBM for measuring GM volumes (e.g., Mechelli et al., 2004) or DTI for investigation of WM tracts and myelination (e.g., Cummine & Boliek, 2013). Each of these studies has revealed different neural regions showing plasticity in bilinguals, including the left inferior parietal lobule (Mechelli et al., 2004), the ACC (Abutalebi et al., 2012) and the anterior midbody of the CC (Coggins et al., 2004).

One of the main problems in studies on structural plasticity in the bilingual brain is that they are rather exploratory in nature, which means that a theoretical foundation for the nature of these changes is lacking. Studies in other domains, such as navigation and music, have revealed that structural changes follow functional demands (Draganski et al., 2004). A first example of this principle was given by a VBM study of taxi drivers in London (Maguire et al., 2000). The functional demand to know all streets and traffic data in the British capital city was related to higher GM volumes in the posterior hippocampus, a region that underlies navigation-related skills. Moreover, a positive correlation was found between the number of months an individual had been employed as a taxi driver and the increase in GM volumes. A second example comes from the musical domain. Elbert et al. (1995) demonstrated that professional violinists had larger cortical representation areas for the fingers used in playing that instrument than non-musicians. These studies provide a theoretical foundation for structural changes in the brain: exactly in those regions that underlie the
skills that are critically needed for performing a specific job or craft, structural changes will be found.

What are the functional demands of bilingual language use that may induce structural changes? Three different types of bilingualism-related demands may be isolated: linguistic, motor and language control demands. The lexical resources that are needed to store lexical items in more than one language are an example of extra linguistic demands. Mechelli et al. (2004) reported increased GM volumes in bilinguals' left inferior parietal lobule. This region is involved in lexical processing, and its size correlates with vocabulary size in monolinguals (Lee et al., 2007). Bilingualism also poses additional articulatory demands on an individual. This is related to increased GM density in the left putamen of trilinguals, a region involved in motor control over production of a less proficient language (Robles et al., 2005). Similarly, the higher needs for phonetic capacity might trigger structural changes in the anterior midbody of the CC, a region that is crucial for mouth and lip adjustments (Coggins et al., 2004). Finally, higher demands regarding the need to control different language systems may result in structural changes to different components of the language control neural network, such as the ACC (Abutalebi et al., 2012) and the caudate nucleus (Cummine & Boliek, 2013).

Another important question is how much bilingual exposure is needed to observe differences with monolinguals. Luk et al. (2011a) reported that lifelong bilingualism enhances WM integrity in older adults, which might be responsible for a delay in the clinical manifestation of dementia (Bialystok et al., 2007; Craik et al., 2010). However, it is unclear at what age these advantages manifest themselves. Behavioural studies have revealed that cognitive advantages to bilingualism are most prominent in children as young as five years old and in older adults, possibly because these effects are attenuated when an individual is at the peak of his attentional abilities in early adulthood (Bialystok et al., 2004). While many studies have investigated neuroplasticity in bilingual older adults (Bialystok et al., 2007; Craik et al., 2010; Luk et al., 2011a), no neurostructural studies so far have been conducted with bilingual children as participants. Furthermore, bilingual effects might be different for various bilingual populations. One study investigating bilingual effects on aging only found language-related
effects in one specific group of multilinguals, but not within a bilingual population (Chertkow et al., 2010).

The present study

This study investigates the neurostructural correlates of bilingualism by measuring FA values in WM pathways of three bilingual populations of eight to ten year old children and age-matched monolingual controls. The Bilingual Enriched Environment hypothesis predicts bilingualism-related structural plasticity in those regions that are most critically needed in bilingual language use. This hypothesis was examined in three WM pathways that are involved in linguistic and motor processing, respectively (see Figure 3.7).

The first pathway was the left arcuate fasciculus/superior longitudinal fasciculus (lAF/lSLF) that connects Broca’s area in the opercular and triangular regions of the left IFG to the posterior language zones in the temporal gyri (Catani and Mesulam, 2008; Catani et al., 2002, 2005). The AF is essential for normal language processing: disconnection of this pathway has been linked to impaired repetition (Catani et al., 2005).

A second pathway is the ventral connection provided by the inferior fronto-occipital fasciculus (IFOF) (Duffau et al., 2002, 2005; Parker et al., 2005). The left IFOF is a large bundle that connects the inferolateral and dorsolateral frontal cortex with the posterior temporal and occipital lobe, extending below the insula and along the inferolateral edge of the claustrum (Catani et al., 2002; Jellison et al., 2004). The left IFOF is known to play a major role in language semantic processing (Duffau et al., 2005; Leclercq et al., 2010; Mandonnet, Nouet, Gatignol, Cappelle, & Duffau, 2007; Rodrigo et al., 2008).

A third pathway was formed by the fibres emerging from the anterior midbody (AMB) of the CC that associate with the premotor and supplementary motor cortices (AMB-PMC). The AMB of the CC has been shown to be larger in bilinguals (Coggins et al., 2004), possibly because it underlies mouth and lip adjustments that are needed for storing the higher bilingual phonetic capacity.
1.1 Methods

Participants. A total of 54 right-handed children (mean age = 9 years, 5 months, \(SD = 11\) months; 24 males, 30 females) was selected for this study. Handedness was defined using the Edinburgh Handedness Inventory (Oldfield, 1999). Based on their language background and age of second language acquisition, participants were subdivided into 15 monolingual children (6 males, 9 females, mean age = 9 years; 7 months; \(SD = 3\) months), 16 sequential bilingual children (8 males, 8 females; mean age = 9 years; 5 months; \(SD = 15\) months) and 23 simultaneous bilingual children (10 males, 13 females; mean age = 9 years; 5 months; \(SD = 11\) months). More information is given in Part One, chapter 2, section 1.1.1. Within the sample of simultaneous bilinguals (n = 23), a new distinction was made according to the number of languages spoken between speakers of two languages (simultaneous bilinguals, n = 11; 4 males, 7 females) and speakers of three or more languages (multilinguals, n = 12; 6 males, 6 females). Multilingual participants spoke three languages on a daily basis: two or three different languages at home and another one or one of these at school.

Wisconsin Card Sorting Task, for a detailed description of this task, see Part One, chapter 2, section 1.1.1 Methods.

Language proficiency. Modified versions from several subtests of the Bilingual Aphasia Test (Paradis et al., 1987) were included in this language
test battery. These tasks can be subdivided into single-language tasks (L1 & L2), an interference task (L1 & L2) and a translation task, in both directions. More information is given in Part One, chapter 2, section 1.1.1.

**Image acquisition.** All scans were done with a Philips Achieva 3 T MR system (software release 2.5), with an 8 channel SENSE head coil. Diffusion weighted images were acquired using a single-shot, echo-planar Stejskal-Tanner sequence with 15 non-collinear diffusion gradient directions and b=700 s/mm². For further technical information, see Mohades et al. (2012).

**Image analysis.** DTI Studio, a program written in visual C++ at the Johns Hopkins University was used for post-processing (Jiang, van Zijl, Kim, Pearlson, & Mori, 2006). The diffusion weighted images were imported in DTI Studio in PAR/REC format. Then, the corresponding gradient table (i.e., the list of vectors that describe the diffusion weighting directions to use for analysis) was calculated using the DTI gradient table creator developed by Farrell et al. (Farrell et al., 2007). For each voxel, the apparent diffusion coefficients (ADC), the diffusion tensor eigenvectors and eigenvalues (λ₀, λ₁, λ₂) and fractional anisotropy (FA) were calculated. FA was defined by

\[
FA = \sqrt{\frac{3}{2}} \cdot \sqrt{\frac{(\lambda_0 - \lambda)^2 + (\lambda_1 - \lambda)^2 + (\lambda_2 - \lambda)^2}{\lambda_0^2 + \lambda_1^2 + \lambda_2^2}}
\]

where \( \lambda = \frac{\lambda_0 + \lambda_1 + \lambda_2}{3} \).

Color maps combining the values of FA (brightness) and the directional information (color coding: left-right in red; anterior-posterior in green and head-foot in blue) for the principal eigenvector for each voxel were derived.

The FACT algorithm (Fiber Assignment by Continuous Tracking) available in DTI Studio was used to reconstruct three-dimensional fibre tracts. This algorithm was reported to be a reliable tool for reconstructing the neuroanatomical fibre tracts (Jiang et al., 2006; Mori & van Zijl, 2002). In this approach, the starting point for fibre tracking is the center of a voxel that has an FA value exceeding a user-defined threshold (0.25 in our study). The tracking proceeds along the direction of the principal eigenvector of
the voxel. At voxel boundaries, the tracking direction is changed to the direction of the principal eigenvector of the neighboring voxel. The end point of the tract is the first voxel that has an FA value lower than a user-defined threshold (chosen to be 0.20, in order to track the fibres into the GM), or at which the tract deviates by more than a given angle (40 in our study).

The next step was to interactively select the fibres passing through the predefined ROIs for each of the four bundles of interest. These ROIs were manually drawn for every individual on the FA weighted color maps (see Figure 3.9). The lAF/SLF was derived by a two-ROI approach using the AND function of the fibre tracking package. The two ROIs were situated: 1) at the level of the rolandic operculum in coronal view; 2) laterally to the ventricular trigone on an axial view. Fibres that pass through both regions defined the lAF/ISLF. To track the lIFOF, an occipital ROI was drawn in a coronal slice, behind the splenium of the CC and a second frontal ROI was drawn on a coronal slice located half-way between the genu of the CC and the anterior margin of the insula. This approach allowed separation of this tract from the lAF/ISLF. The AMB-PMC bundle was found by drawing a single ROI in the AMB of the CC (Coggins et al., 2004).

Quantitative and statistical analysis. SPSS 17.0 was used for all statistical analyses. For each of the three bundles, the mean and standard deviation of the FA values of all the voxels within the bundle were calculated. To assess the significance of group differences in mean FA between multilinguals, simultaneous bilinguals, sequential bilinguals and monolinguals, a one-way analysis of variance with Bonferroni-corrected post-hoc testing for multiple comparisons was undertaken. Scores from 9 multilinguals, 9 simultaneous bilinguals, 13 sequential bilinguals and 13 monolinguals could be used for further analysis. Differences were considered significant for p-values less than .05. In order to establish the normality distribution of the samples, one-sample Kolmogorov-Smirnov tests were conducted on all dependent variables. Based on the p-values of these analyses, parametric (p-value > 0.05) or non-parametric tests (p-value < 0.05) were carried out.
1.2 Results

A one-way analysis of variance did not show any between-group differences in age, \(F(3,50) = .81, p > .05\), gender, \(X(3) = .76, p > .05\), or socioeconomic status, \(X(3) = 19.33, p > .05\). Differences in intelligence were controlled for by an equal number of perseverative errors, \(F(3,49) = .30, p > .05\), non-perseverative errors, \(F(3,49) = 2.43, p > .05\), total errors, \(F(3,52) = 1.55, p > .05\), and trials to complete the first category, \(F(3,52) = 1.74, p > .05\), on the Wisconsin Card Sorting Test across the four different groups. The bilingual participants were also matched on proficiency, as described in Part One, chapter 2, section 1.1.2.

The three bundles of interest could be traced for all subjects, with one exception: in 4 participants the IAF/ISLF could not be drawn consistently. Table 3.1 lists for each group the mean FA values for the three bundles and their standard deviations. The distribution of data is illustrated in error-bar plots for each bundle of fibres (see Figure 3.8).

<table>
<thead>
<tr>
<th></th>
<th>MONO.</th>
<th>SEQ. BIL.</th>
<th>SIM. BIL.</th>
<th>MULTI.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAF/SLF</td>
<td>.52 (.04)</td>
<td>.53 (.04)</td>
<td>.53 (.03)</td>
<td>.52 (.03)</td>
</tr>
<tr>
<td>IIFOF</td>
<td>.52 (.03)</td>
<td>.52 (.03)</td>
<td>.54 (.02)</td>
<td>.56 (.02)</td>
</tr>
<tr>
<td>AMB-PMC</td>
<td>.57 (.02)</td>
<td>.58 (.02)</td>
<td>.58 (.03)</td>
<td>.57 (.02)</td>
</tr>
</tbody>
</table>

Table 3.1 Mean FA values in three bundles of fibres according to language group. Standard deviations are given between brackets.

One-way analyses of variance with the four groups as independent variables and the mean FA values of the four different bundles as dependents revealed a significant group effect on IOF WM microstructure, \(F(3,43) = 5.00, p < .01\), but not on AF, \(F(3,43) = .11, p > .05\), nor on AMB-PMC, \(F(3,40) = .50, p > .05\). Bonferroni-corrected post-hoc analyses revealed that the differences in IOF microstructure were only present between multilinguals and monolinguals (\(p < .01\)) and between multilinguals and sequential bilinguals (\(p < .05\)).
Figure 3.8 Mean FA values for three bundles of fibres according to language group. Error bars represent 95% confidence interval.
1.3 Discussion

The present study investigated the neurostructural correlates of bilingualism by measuring FA values in WM pathways of three bilingual populations of 8 to 10 year old children and age-matched monolingual controls. The results confirmed the Bilingual Enriched Environment hypothesis: on at least one of the selected pathways, specific bilingual populations showed higher FA values than age-matched monolinguals. Differences in mean FA values can be linked to features of neuronal structure, such as the number of axons, axon density, size of axons and degree of myelination (see Mohades et al., 2012). Besides, FA values correlate with information transmission properties (Böhr et al., 2007), and with cognitive and information processing speed (Penke et al., 2010; Turken et al., 2008).

Significant between-group differences were only found on the lIFOF and not on any of the two other selected pathways. Pairwise comparisons revealed that FA values in the lIFOF were higher for multilinguals than for monolinguals and sequential bilinguals. Higher anisotropy of WM over the lIFOF in multilinguals supports the idea that the semantic processing and transmission of semantic information in multilinguals might be subserved by more or denser axons that are in charge of more efficient interneuronal communication. This is a good illustration of the general neurostructural principle that structural changes follow functional demands. Multilinguals need to process more lexical items and semantic information which requires additional neuronal tissue.

Interestingly, the pathway most affected by bilingualism connects the dorso- and inferolateral PFC to posterior regions in the temporal and occipital lobes. The dorsolateral PFC forms part of a language control network that is reliably activated in bilingual language tasks (Abutalebi & Green, 2007). Little is known about the exact functions of this pathway, yet further investigations could assess if the observed differences are related to the additional functional demands that are associated to controlled processing in bilinguals.

No further differences were found on any of the two other pathways that were examined. One possible reason was that one of these, the lAF/lSLF, could not be reconstructed in some of the participants. The AF has been
reported to continue to myelinate until the later stages of life. In a recent study, Brauer, Anwander and Friederici (2011) have reported a significantly lower anisotropy in children's AF/SLF compared to adults, supporting the immature status of this pathway in children. Irrespective of the underlying cause of the null effect, no evidence was found for bilingualism-related structural differences in the AF or AMB/PMC. It might be that these pathways fulfill functional roles that are not specifically involved in bilingual language behaviour.

Another important conclusion of this study is the observation that the IIFOF microstructure is different in the three bilingual groups even though their second language proficiency was controlled for. Multilinguals showed higher fractional anisotropy than sequential bilinguals but not than simultaneous bilinguals. Logically, the number of daily used languages may modulate the demands on semantic processing. What then may be the explanation for the differences between simultaneous and sequential bilinguals? Previous linguistic research has shown that simultaneous bilinguals outperform sequential children on their overall vocabulary size (either-language method). A possible reason for this is that the two languages of a simultaneous bilingual are not functionally distributed across different language environments. Indeed, simultaneous bilinguals speak two languages at home, whereas sequential bilinguals only speak one language at home and another one at school. If the FA values on the IIFOF correlate to semantic processing, it may be expected that those groups with highest demands regarding semantic processing show most structural plasticity.

Finally, our results show that differences in neurostructure may arise at very young age. Sequential bilinguals already started acquisition of the second language around age two. Still, their FA values in the IIFOF were significantly lower than multilinguals and comparable to monolinguals. This impact of the age of acquisition could be expected because the main process of myelination in the human brain occurs in early childhood, before the second year of life (Lenroot and Giedd, 2006).
2. Cross-sectional study I

The Bilingual Enriched Environment hypothesis predicts bilingualism-induced structural plasticity in regions that are highly relevant for bilingual language processing. However, the communicative environments in which bilingual proficiency is achieved are different for every individual. In a study with a group of American-born exchange students who acquired German in a naturalistic and immersion setting in Switzerland, significant correlations were found between their progress in second language proficiency and an increase in GM density in the IFG (Stein et al., 2012). Another study investigated brain development in interpreters during an intensive linguistic training (Martensson et al., 2012). Training effects were detected in a number of language-related neural zones such as the left IFG, middle frontal gyri, and the STG.

Figure 3.9 Location of ROIs to trace specific fibres. Cyan ROIs (A and B) are those to trace lAF/ISLF, red ROIs (D and E) to trace lIFOF, and the yellow ROI (C) to trace AMB-PMC.
Lifelong bilingualism in contrast appears to induce structural plasticity in other parts of the brain. These parts include the left inferior parietal lobule (Mechelli et al., 2004), the putamen (Abutalebi et al., 2013a) or the ACC (Abutalebi et al., 2012). These are regions outside the classical language zones that supposedly underlie lexical processing (Lee et al., 2007) or language control (Abutalebi & Green, 2007). All of these studies compared properties of GM in the brains of monolinguals and bilinguals.

Studies on WM differences have not been able to replicate these results. Cummine & Boliek (2013) found no regions of increased FA values in a group of bilingual young adults who started acquisition of their second language around age five. Coggins et al. (2004) detected a significant difference between bilinguals and monolinguals in the AMB of the CC. This was related to the higher needs for phonetic capacity in multilingual participants. Interestingly, a similar hypothesis was put forward for explaining higher GM density in the left putamen (Abutalebi et al., 2013a). Again, this illustrates the principle that structural changes follow functional demands. The larger articulatory load of speaking more than one language can result in higher GM density in motor control regions such as the putamen and to differences in WM microstructure in the connections between the AMB of the CC and the premotor cortex.

The present study

This study investigates the differences in short- and long-term neural adaptations to intensive bilingual language use in the WM microstructure of simultaneous bilinguals and interpreters with equal listening and writing proficiency in their second language. The crucial distinction between both groups was their length of exposure to a second language. Evidently, the simultaneous bilinguals had been using the other language for their entire life, while the interpreters had started acquisition of the other language at later age. In order to assess the effects of lifelong bilingualism on neural structure, FA values were measured in three WM pathways. The main question is whether linguistic or motor control processing are affected most by lifelong bilingualism.
2.1 Methods

Participants. A total of 17 right-handed healthy bilinguals (mean age = 23 years, 8 months; SD = 1 year, 9 months; 8 males, 9 females) without any neurological dysfunction were recruited for this study. The protocol had been approved by the Ethics Committee of the University Hospital of Brussels (UZ Brussels, Belgium). Based on an extensive language questionnaire, participants were classified into simultaneous bilinguals and interpreters. Simultaneous bilinguals (n = 9) had acquired two languages from birth onwards. The native tongues of simultaneous bilinguals were Dutch (n = 6), English (n = 2) and Rumanian (n = 1). Their second languages included French (n = 5), Dutch (n = 2), English (n = 1) and Spanish (n = 1). They reported daily use of their second language accompanied by excellent listening, speaking and reading skills and very good writing skills. Interpreters (n = 8) were enrolled in an intensive linguistic programme. The native language of all interpreters was Dutch. Their second language was either English (n = 5) or French (n = 3). In contrast to the simultaneous bilinguals, their mean age of second language acquisition was seven years and eleven months (SD = 3 years; 8 months). An independent samples t-test revealed that this difference was highly significant, t(15) = -4.90, p < .001.

Image acquisition and Image analysis, see 1.1.

Quantitative and statistical analysis. SPSS 17.0 was used for all statistical analyses. For each of the three bundles, the mean and standard deviation of the FA values of all the voxels within the bundle were calculated. To assess the significance of group differences in mean FA between simultaneous bilinguals and interpreters, an independent samples t-test was carried out. Differences were considered significant for p-values less than 0.05. In order to establish the normality distribution of the samples, one-sample Kolmogorov-Smirnov tests were conducted on all dependent variables. Based on the p-values of these analyses, parametric (p-value > 0.05) or non-parametric tests (p-value < 0.05) were carried out.


### 2.2 Results

**Demographics.** An independent samples T-test did not show any difference in age, \( t(15) = -1.80, p > .05 \). A chi-square test showed that also gender distributions were equal for the two groups, \( \chi^2(1) = .55, p > .05 \).

**Language proficiency.** Interpreters reported very good listening, speaking, reading and writing skills in L2. Mann-Whitney U tests revealed that L2 speaking, \( U(15) = 13.00, Z = -2.40, p < .05 \), and reading skills, \( U(15) = 16.00, Z = -2.22, p < .05 \), were significantly different for both groups, with higher self-reported proficiency for the simultaneous bilinguals than for the interpreters. L2 listening and writing did not show any differences between the groups. Interpreters also reported the length of their interpreter’s training. There was huge variability with the length of training ranging from seven months to five years and eight months (\( M = 1 \) year; 10 months; \( SD = 1 \) year; 8 months).

**Fibre tracking.** The bundles could be traced for all subjects. Table 3.2 lists for each group the mean FA values for the three bundles of interest and their standard deviations. An independent samples t-test with the two groups as independent variables and the mean FA values of the three different bundles as dependents revealed a significant group effect on AMB-PMC WM microstructure, \( t(15) = 2.25, p < .05 \), but not on lIFOF, \( t(15) = .53, p > .05 \), or on AF, \( t(15) = 1.04, p > .05 \).

<table>
<thead>
<tr>
<th></th>
<th>SIM. BIL.</th>
<th>INTERPRETERS</th>
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<tbody>
<tr>
<td>AMB-PMC</td>
<td>.61 (.02)</td>
<td>.59 (.01)</td>
</tr>
<tr>
<td>lIFOF</td>
<td>.56 (.01)</td>
<td>.56 (.03)</td>
</tr>
<tr>
<td>AF</td>
<td>.56 (.02)</td>
<td>.55 (.02)</td>
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</table>

*Table 3.2 Mean FA values in three bundles of fibres according to language group.*

### 2.3 Discussion

The present study investigated the neurostructural correlates of lifelong bilingualism by measuring FA values in WM pathways of two populations of bilingual young adults. The first group was formed by simultaneous bilinguals who had been exposed to both languages from birth onwards. The second group was composed of interpreters who used their second
language daily on a professional basis. Crucially, both groups were matched for proficiency in order to isolate the effects of length of exposure.

Significant differences were found on WM microstructure in the connections between the AMB of the CC and the premotor cortex. The AMB was the callosal region reported to have a larger size in bilinguals compared to monolinguals (Coggins et al., 2004). The hypothesis was put forward that the higher needs for phonetic processing in bilinguals might be subserved by more neuronal tissue in the region that is responsible for this skill. The results of the present study appear to further support the importance of the connections between the CC and motor areas subserving mouth and lip movements for bilingualism. Furthermore, these results are in line with the idea that the higher articulatory load associated to multilingualism induce structural plasticity in regions that subserve motor control over language production (Abutalebi et al., 2013a).

In contrast, no differences were found in the two other pathways under investigation, one of which was shown to be significantly different between simultaneous and sequential bilingual children (see section 1.2). It should be reminded that FA values in this region were associated with the speed and efficiency and semantic processing. Logically, interpreters exactly need these skills to perform their job. Future studies could find out whether other high-proficient sequential bilinguals without interpreting experience show lower FA values in the IFOF than simultaneous bilinguals.

The design of this study comparing two groups of proficiency-matched bilinguals with different lengths of exposure to the second language allowed for a better understanding of bilingualism-induced structural plasticity. Coggins et al. (2004) already showed that the size of the AMB of the CC is significantly different between bilinguals and monolinguals. The present study has shown that specifically lifelong bilingualism drives this structural plasticity by revealing similar differences between two proficiency-matched groups of bilinguals. The finding that onset age of acquisition affects exactly a region involved in motor control over language production is not surprising. Accent has been one of the most studied topics in the field of critical periods and language attainment (e.g., Flege et al., 1995). It has been asserted that a native-like accent is one of the aspects of language processing that is most difficult to acquire for late learners (see for a review, Singleton, 1989). The results of our study may give an
Neurostructural effects of bilingualism

explanation for this. Higher FA values in the regions that underlie speech production are long-term and no short-term neural adaptations to bilingualism. This means that a significant length of exposure is needed to observe structural plasticity in late learners of a second language, even if they have already attained high proficiency in that language. Future studies could find out the neurostructural correlates of individual variability in the attainment of native-like accent in sequential bilinguals. Furthermore, the question can be examined what amount of exposure is needed to see equal FA values between early and late learners.
This chapter investigated the effects of bilingualism on neural structure. The hypothesis was put forward that bilingualism is one of the factors that contribute to an enriched environment. This hypothesis has previously been tested by using VBM for measuring GM concentrations (Mechelli et al., 2004) or DTI for visualizing properties of WM pathways (Cummine & Boliek, 2013). Yet, the functional demands that cause structural changes in the bilingual brain remain elusive. Three different types of demands can be distinguished: language-related factors such as those involved in lexical processing or the articulatory repertoire (Mechelli et al., 2004; Abutalebi et al., 2013a), factors related to motor control such as the additional requirements regarding the phonetic capacity (Coggins et al., 2004), and the reliance on the language control network (Abutalebi et al., 2012; Cummine & Boliek, 2013). Two studies were reported in this part that tried to find out what type of brain structures is affected by bilingualism. An overview of the results from these studies can be found in Table 3.3.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>CONTRAST SHOWING SIGN. DIFFERENCES</th>
<th>WM PATHWAY AFFECTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal study, T1</td>
<td>Multilinguals &gt; sequential bilinguals; multilinguals &gt; monolinguals</td>
<td>IFOF</td>
</tr>
<tr>
<td>Cross-sectional study I</td>
<td>Simultaneous bilinguals &gt; interpreters</td>
<td>AMB/PMC</td>
</tr>
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</table>

Table 3.3 Overview of results from studies reported in Part Three.

In a first study, three populations of bilingual children were compared to age-matched monolingual controls. Only the multilinguals but not the simultaneous bilinguals showed higher WM integrity than the monolingual group in the left IFOF. This language-relevant WM pathway plays an important role in lexical processing. The number of languages spoken appears thus to be the relevant factor. Surprisingly, a same significant difference was found between the multilinguals and the sequential
bilinguals. These results were explained by referring to the lower functional demands related to lexical processing in bilinguals with functionally distributed lexicons. Indeed, sequential bilinguals tend to use different language systems, and possibly also slightly different vocabularies, for school and home settings (Cummins, 2008). On the contrary, multilinguals use at least three languages on a daily basis, and some of them in overlapping communicative contexts. Logically, this raises the need for additional neural connections that are in charge of rapid language processing.

In a second study, early simultaneous bilinguals were compared to proficiency-matched late-acquisition interpreters in order to isolate the effects of lifelong bilingualism. Higher FA values in simultaneous bilinguals were detected in one specific WM pathway linking the AMB of the CC to the premotor cortex. Previous studies had linked the size of this neural structure to bilingualism (Coggins et al., 2004). Functionally, the AMB of the CC has been proposed as subserving lip and mouth adjustments that are needed to implement the higher phonetic capacity of proficient bilinguals. Future studies could further investigate if a possible link can be made with the observation that a native-like accent is one of the aspects of language processing that is difficult to acquire for late L2 learners, even when they are high-proficient and daily users of that language.
Part Four
A combined socio- and psycholinguistic theory of controlled processing in bilinguals: behavioural and neural correlates
The need to manage two or more languages in the bilingual mind is assumed to have an impact on domain-general controlled processing (Hilchey & Klein, 2011). Lately, however, the presence of bilingual advantages in cognitive control has been challenged by a number of studies showing no differences between monolinguals and bilinguals on measures of cognitive control (Costa et al., 2009; Morton & Harper, 2007; Paap & Greenberg, 2013). These contradictory outcomes have been attributed to a wide variety of factors such as subtle differences in the features of the tasks (Bialystok et al., 2006), in the sociolinguistic environment of the participants (Costa et al., 2009) or in their demographics such as migration background or socioeconomic status (Morton & Harper, 2007).

From a theoretical viewpoint, there have been many considerations on the nature of the cognitive control component that is related to bilingualism (Costa et al., 2009; Hilchey & Klein, 2011). Regrettably, there has never been proposed a theoretical framework for understanding the linguistic factors that drive the bilingual advantage. Therefore, this section presents a combined socio- and psycholinguistic theory of controlled processing in bilinguals. Combining research data from recently published articles and the results described in this dissertation, this section will argue that contradictory outcomes can be explained by individual variability in bilinguals’ language control abilities. The hypothesis goes that these differences are not genetic in nature, but that specific sociolinguistic environments contribute to the development of these skills.

This part is composed of five sections. First, a definition of cognitive control is given. Second, the question which cognitive control component is affected most by bilingualism is answered. Third, the psycholinguistic part of the proposed theory is elaborated on by looking at the effects of language control abilities on cognitive control in bilinguals. Fourth, the sociolinguistic part of the theory is attended to by investigating which language sociological factors contribute to these language control abilities. To conclude, a number of future directions are suggested to test and refine the presented theory.
1 What is controlled cognitive processing?

Controlled cognitive processing (or cognitive control or executive functioning) refers to the ability of humans to swiftly adapt their behavior to a changing environment. Flexibility is needed when automatic behaviour has to be turned off, when a laid down plan has to be modified or when an effortful action should be preferred over a more readily available one (Norman & Shallice, 1980). Behaviourally, controlled processing incurs a cost in terms of response times and accuracy (Eriksen & Eriksen, 1974; Kornblum et al., 1990; Simon & Rudell, 1967). Controlled processing appears to activate a specific neural network including the prefrontal cortex (PFC) and the anterior cingulated cortex (ACC) (Alvarez & Emory, 2006; Botvinick et al., 2001).

Theoretical models have proposed different conceptualizations of cognitive control and its components. Fan et al. (2002) considered cognitive control (or executive functioning) as one component of an attentional network that also includes functions of orienting and alerting. Miyake et al. (2000) proposed a model of cognitive control that was composed of three distinct but interrelated components: inhibition, shifting and updating. Bunge et al. (2002) suggested another distinction between interference suppression and response inhibition. Finally, the Conflict Monitor hypothesis predicts an important distinction between the functions of the ACC and the PFC: while the ACC would operate as a monitor that signals the need for controlled processing, the PFC supposedly underlies these processes themselves (Botvinick et al, 2001).

2 Which cognitive control component is affected by bilingualism?

2.1 What can be learnt from previous behavioural studies?

Using the theoretical models mentioned in the previous paragraph, researchers have tried to relate bilingual effects to specific components of cognitive control. Bialystok (2009) argued that only the ‘inhibition’ and ‘shifting’ but not the ‘updating’ component of the model proposed by Miyake et al. (2000) are affected by bilingualism. Indeed, on those trials of
conflict tasks that require *inhibition* of automatic but non-target responses, bilinguals appear to outperform monolinguals (Bialystok et al., 2004; Bialystok, 2006; Martin-Rhee & Bialystok, 2008). In addition, a similar advantage is also visible on *switch* trials in paradigms where participants have to alternate between different tasks (Garbin et al., 2010). In contrast, working memory tasks do not show a similar bilingual advantage (Fernandes et al., 2007). Luk et al. (2010) further confined the bilingual effects in inhibition to *interference suppression*, one of the two controlled processing components proposed by Bunge et al. (2002).

Also bilingual processing can be divided into various components, each of which is associated with different control requirements. Recently, three crucial bilingual skills were distinguished by Paap & Greenberg (2013). First, bilinguals need to *inhibit* lexical items from their non-target language when they process the target language. This is in line with the extensive available literature that shows simultaneous activation of two language systems during bilingual language processing (see, for an overview, van Heuven & Dijkstra, 2010). Second, bilinguals have to be able to *switch* smoothly between their two languages, such as during translation, interpreting or code switching. Voluntary language switches in bilingual language use are known to occur rather frequently and to serve communicative purposes (Rodriguez-Fornells et al., 2011). Third, bilinguals are required to *monitor* their communication environment for signals that indicate when language switches are appropriate or not. The first two aspects of bilinguals’ language use - inhibition of non-target language items and switching between languages - may be related to the ‘inhibition’ and ‘shifting’ components of Miyake’s et al. (2000) model, whereas the monitoring aspect relies on the conflict monitor in charge of determining when cognitive control is needed (Botvinick et al., 2001).

Most evidence for bilingual advantages in each of these three components has come from conflict tasks, such as the colour Simon or Flanker tasks (see, for an overview, Hilchey & Klein, 2011). Conflict tasks are typically composed of conflict or incongruent, and non-conflict or congruent trials. On incongruent trials, the correct response requires inhibition of the automatically triggered response. Therefore, incongruent trials need more processing time and accuracy on these trials is lower (Kornblum et al., 1990). Based on a review of studies on bilinguals’ performance on conflict
tasks, Hilchey & Klein (2011) proposed a distinction between the two following types of bilingual advantages: a Bilingual Inhibitory Control Advantage (BICA) and a Bilingual Executive Processing Advantage (BEPA) (see, for an overview, Table 4.1). Logically, an effect on inhibition would manifest itself most prominently in incongruent trials because they require most controlled inhibition. Statistically, this is indicated by a significant interaction effect between group (bi- versus monolinguals) and congruence (congruent versus incongruent). However, only a small minority of all studies on bilinguals’ cognitive control has found evidence for this interaction (Bialystok et al., 2004; Salvatierra & Rosselli, 2010).

The BEPA hypothesis predicts bilingual advantages on both congruent and incongruent trials. Indeed, a number of studies have found a significant main effect of group with faster and more accurate responses for bilingual participants, without an interaction effect between group and congruency (Bialystok et al., 2005a; Costa et al., 2008). The term BEPA is rather misleading because a main effect of bilingualism does not mean that executive processing (or cognitive control) is affected as a whole. Actually, congruent trials are not at all assumed to tap controlled cognitive processing. This means that another type of controlled cognitive processing underlies the perceived main effect on congruent and incongruent trials.

<table>
<thead>
<tr>
<th>RELEVANT SKILL</th>
<th>STATISTICS</th>
<th>TYPE OF ADVANTAGE</th>
<th>EVIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhibition</td>
<td>Interaction effect group x congruency</td>
<td>BICA</td>
<td>Bialystok et al., 2004; Costa et al., 2008; Costa et al., 2009; Salvatierra &amp; Rosselli, 2010</td>
</tr>
<tr>
<td>Switching</td>
<td>Interaction effect group x switching</td>
<td>BCSA</td>
<td>Costa et al., 2008</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Main effect group</td>
<td>BEPA</td>
<td>Bialystok et al., 2005b; Bialystok, 2006; Emmorey et al., 2008; Martin-Rhee &amp; Bialystok, 2008; Costa et al., 2008; Costa et al, 2009</td>
</tr>
</tbody>
</table>

Table 4.1 Overview of controlled processing skills that are relevant for bilinguals (see Paap & Greenberg, 2013).
Monitoring has been suggested as the crucial skill that underlies the BEPA. This hypothesis was tested by using high- and low-monitoring variants of the Flanker task in a bilingual population (Costa et al., 2009). The difference between these two variants was the ratio of congruent-to-incongruent trials. In high-monitoring contexts, the two types of trials were equally distributed with a high amount of congruent-to-incongruent or incongruent-to-congruent switches; in low-monitoring contexts, one of the two trial types was more prominent, with a lower number of congruence switches. Bilingual effects were only seen in the high-monitoring contexts. In addition, the bilinguals were quicker on the incongruent trials that were preceded by congruent ones (switch trials) than on those preceded by incongruent trials (repeat trials). This advantage can be labeled as a Bilingual Congruence Switching Advantage (BCSA). The generalizability of this effect remains under debate (Paap & Greenberg, 2013).

2.2 What can be learnt from previous neuroimaging studies?

A better insight into the bilingual effects on controlled processing can be deduced from neuroimaging studies. The Bilingual Neural Overlap hypothesis states that there will be a degree of overlap in the neural regions that bilinguals use for language control and for domain-general cognitive control. Regions known to be involved in language control include the PFC, the ACC, the caudate nucleus and the left inferior parietal lobule (Abutalebi & Green, 2007, see chapter 2.1), mostly lateralized to the left hemisphere. The hypothesis goes that bilingualism induces functional plasticity in regions of the neural language control network so that they can be used for efficient domain-general controlled processing (Abutalebi et al., 2012).

Functional neuroimaging studies have confirmed the Bilingual Neural Overlap hypothesis. Bialystok et al. (2005a), Garbin et al. (2010) and Luk et al. (2010) found higher recruitment of the left inferior PFC in bilingual participants on different measures of cognitive control including incongruent trials of the Simon or Flanker task and switch trials of a non-linguistic task switching paradigm. The interaction between the behavioural advantages in bilinguals and the neural circuitry underlying this enhanced processing remains unclear. While Garbin et al. (2010)
reported enhanced switching skills in the bilingual participants, Bialystok et al. (2005a) and Luk et al. (2010) did not detect any bilingual advantage.

Their extensive use of monitoring processes may also affect the neural correlates of bilinguals’ controlled cognitive processing. Abutalebi et al. (2012) were the first to report specific bilingual effects on the ACC, the region assumed to function as a conflict monitor (Botvinick et al., 2001). Not only did bilinguals recruit the ACC less extensively than monolinguals on incongruent trials of the Flanker task, they were also found to use this structure more efficiently than monolinguals. Whereas monolinguals showed more activity in this region in the second than in the first session of the Flanker task, bilinguals showed a significant drop in ACC activity. These within-task training effects were confirmed by the behavioural data: the declines in response times between both sessions were significant for the bilingual group, but not for the monolinguals.

All these studies lead to the conclusion that the PFC and the ACC are differently affected by bilingualism. While additional involvement of the PFC might facilitate cognitive control in bilinguals (Bialystok et al., 2005a; Garbin et al., 2010), the ACC is tuned by bilingualism so that less activity is needed to perform the same control task (Abutalebi et al., 2012).

### 2.3 What has this dissertation contributed?

This dissertation reported a number of studies in which three different conflict tasks were used: the numeric Stroop task (Kaufmann et al., 2008; Tzelgov et al., 1992), the Flanker task embedded in an Attention Network Test (Fan et al., 2002) and the two-colour Simon task (Simon & Rudell, 1967). In all tasks, congruent and incongruent trials were equally distributed. A crucial conclusion is that no evidence was found for an effect on inhibition, as indicated by significant interaction effects between group and congruence, neither in children nor in young adults.

In contrast, main group effects on overall performance were detected, but only after regrouping the bilingual participants based on their scores on a mixed-language task. This effect was observed both in children and in adults. The hypothesis was tested that congruence switching was the relevant underlying principle. In contrast to previous studies (Costa et al., 2009), the investigation of congruence switching was not restricted to
congruent-to-incongruent switches. Rather, a distinction was made between switch and repeat trials, irrespective of their congruence. This hypothesis was partly confirmed by a nearly significant interaction effect between group and switching, both in bilingual children and young adults.

Further evidence for the relevance of congruence switching for bilingualism-induced differences in controlled cognitive processing comes from neuroimaging. This dissertation reported the first study on the neural correlates of non-linguistic monitoring processes in bilinguals. This was done by investigating the neural contrast between congruence repeat and congruence switch trials. It was found that faster response times on the switch trials were associated with a network including many components of the neural language control network such as the bilateral ACC, the right dorsolateral PFC and the left inferior parietal lobule (compare to Abutalebi & Green, 2007).

3 A psycholinguistic theory of controlled processing in bilinguals: the role of language control abilities

3.1 What can be learnt from previous behavioural studies?

The observation that the bilingual advantage is not present across all different environments is not surprising. There is a huge variation among bilinguals in the age at which they start acquiring their second language, in their manner of acquisition and the proficiency levels they attain. Each of these factors may contribute differently to cognitive control skills. Recently, there has been a shift in the literature towards the investigation of differences within bilingual populations by recruiting bilingual groups with different onset ages of acquisition (Luk et al., 2011b), proficiency levels (Salvatierra & Rosselli, 2010), manners of acquisition (Carlson & Meltzoff, 2008) or language control abilities (Prior & Gollan, 2011). Among all these different factors, language control skills have turned out to be the most reliable predictor of cognitive control (Linck et al., 2012; Soveri et al., 2011). The rationale goes as follows: if constant language management is responsible for the bilingual advantage in cognitive control, the individual
variability in bilinguals’ language control skills might explain why the advantage is only infrequently seen.

<table>
<thead>
<tr>
<th>STUDY</th>
<th>MEASURE(S) LANGUAGE CONTROL</th>
<th>MEASURE(S) COGNITIVE CONTROL</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Festman et al. (2010); Festman &amp; Münte (2012)</td>
<td>Resistance non-target language interference (two-language picture naming)</td>
<td>Tower of Hanoi, Ruff Figural Fluency Task, Divided Attention, Go-Go, WCST, Flanker task</td>
<td>effect of language control</td>
</tr>
<tr>
<td>Linck et al. (2012)</td>
<td>L1, L2, L3 naming &amp; switch costs (three-language picture naming task)</td>
<td>Simon task</td>
<td>effect of language control</td>
</tr>
<tr>
<td>Prior &amp; Gollan (2011)</td>
<td>Self-reported language switching frequency &amp; language switching costs (two- and one-language digit naming)</td>
<td>task-switching paradigm</td>
<td>effect of language control</td>
</tr>
<tr>
<td>Rodriguez-Fornells et al. (2011)</td>
<td>Self-reported language switching behaviour</td>
<td>Stop signal task, colour word Stroop task, Flanker task</td>
<td>effect of language control (only on stop signal paradigm)</td>
</tr>
<tr>
<td>Soveri et al. (2011)</td>
<td>Self-reported language switching behaviour</td>
<td>Simon task, Flanker task, task-switching paradigm</td>
<td>effect of language control (only on task switching)</td>
</tr>
</tbody>
</table>

Table 4.2 Overview of studies that have investigated the BLCE.

The direct link between language and cognitive was demonstrated in a recent study with unbalanced trilinguals. Linck et al. (2012) reported that the size of the congruence effect in the Simon task (incongruent contrasted to congruent trials) predicted performance on a mixed-language picture naming task. More specifically, response times on switch trials from and into L1 appeared to correlate with general-purpose conflict resolution. The generalizability of this effect was challenged by a study with simultaneous bilinguals. Soveri et al. (2011) only detected an effect of language switching behaviour on mixing costs in a task switching paradigm but not on a Simon or a Flanker task. Language switching in this study was established by self-reported measures.
Two other studies have compared bilingual groups with different language control abilities. In both instances, good language controllers also scored better on cognitive control. Festman et al. (2011) tested the effect of language control by comparing two groups of late bilinguals that were distinguished based on their resistance to non-target language interference. The group who made the least interference errors in a mixed-language picture naming task scored better on a number of tasks tapping cognitive control (see, for an overview, Table 4.2). Prior & Gollan (2011) recruited two groups of Spanish-English and Mandarin-English bilinguals, who significantly differed from each other in their (self-reported) frequency of language switching and in switching costs on a mixed-language naming task. In fact, the Spanish-English bilinguals combined more language switching in their daily lives with lower costs on the switch trials of a mixed-language task. This pattern was replicated in a non-linguistic colour-shape switching task: the Spanish-English bilinguals showed significantly lower switching costs than the other two groups, who did not differ from each other.

Whereas frequent language switchers appear to outperform other bilinguals on cognitive control, involuntary language switchers might also show a disadvantage in domain-general controlled processing. Rodriguez-Fornells et al. (2011) used a language switching questionnaire to classify bilinguals according to their (self-reported) switching behavior. Four different constructs were distinguished: switching into L1, switching into L2, contextual switching and unintentional switching. Only the last of the four constructs appeared to correlate with scores on a non-verbal controlled cognitive processing task: individuals who reported more unintentional switches also scored less on a stop signal paradigm used to measure controlled inhibition skills.

All these studies clearly show that individual language control abilities may explain bilingual performance on cognitive control tasks. A few issues have remained unexplored by these studies, however. First, psycholinguistic studies have indicated that the size of switch costs in bilingual tasks may be related to the direction of the switches and the onset age of active bilingualism of the study population. Meuter & Allport (1999) reported higher switching costs for switches into L1 than into L2 in a group of late and unbalanced bilinguals. Costa & Santesteban (2004), in contrast, revealed symmetrical switching costs in a group of early, high-proficient
bilinguals. Interestingly, this symmetry could not be related to differences in proficiency levels between the languages involved. The direct correlation between language switch costs and cognitive control performance (Linck et al., 2012; Prior & Gollan, 2011) leads to the question whether the impact of language control abilities will be the same for early and late bilinguals and whether L1 and L2 switches will be similarly affected.

Second, the above mentioned studies have largely ignored the developmental aspects of bilingualism-induced effects on cognitive control. Studies comparing bilinguals to monolinguals have shown that aging has an impact on bilingual advantages: while they are most prominent in older adults and young children, they tend to be attenuated in early adulthood, when individuals are at the peak of their attentional abilities (Bialystok et al., 2005b; see, for a different view, Morton & Harper, 2007). The development of language control abilities in childhood and late adulthood may be responsible for the observed patterns in studies on bilinguals' controlled processing.

Finally, no study has investigated the neural aspects of the language control effect. The effect of language control abilities on the localization of neural activity during cognitive control processing might be an excellent testing ground for the neural overlap hypothesis which states that bilingualism induces functional plasticity in those regions that are used in mixed-language activities for cognitive control. It was expected that bilinguals with high language control abilities use these regions more efficiently.

3.2 What has this dissertation contributed?

This dissertation confirmed the effect of language control in two separate studies with different age groups. In a study with bilingual young adults, scores on a mixed-language phonemic verbal fluency task were used as a measure of language control abilities. Cluster analysis was used to group all participants into high- and low-proficient language mixers. A main effect of this grouping variable was found on Simon task performance. Furthermore, an individual approach led to the same results: forward switch costs on a mixed-language semantic categorization task significantly correlated with response times on switch trials and incongruent trials of the Simon task. A trend towards an effect on congruence switching was observed with
smaller performance differences between switch and repeat trials for high-proficient language mixers than for low-proficient mixers.

Importantly, only the forward switching but not the backward switching costs turned out to correlate with performance on the Simon task. High-proficient language mixers showed asymmetry in language switching with lower response trials on L2 switch (forward switch) than on L2 repeat trials and lower forward than backward switch costs. This could mean that high-proficient language controllers are more efficient in inhibiting their dominant language, and that this efficiency is accompanied by behavioural advantages that transfer into domain-general controlled processing advantages.

What are the neural correlates of these group differences in forward switching during a mixed-language task? A group comparison of neural activity on the forward switching contrast revealed higher activity for the high mixing proficiency group in the neural language control network, more specifically in the bilateral ACC and the left dorsolateral PFC. This was different from the pattern observed on backward switching, where the low mixing proficiency group showed compensatory additional activity in the right ACC, part of the control network. This unexpected combination of more controlled processing and better performance might explain why code-switching is such an efficient way of communication despite the observation in laboratory settings that it incurs switching costs due to effortful processing. Possibly, bilinguals with good language control abilities have learnt how to use controlled processing in such an efficient way that behavioural facilitation, in terms of reduced mixed-language costs, is accomplished.

This pattern of (behavioural) results was replicated in a study with bilingual children and matched monolingual controls. Mixing costs on the same two-language phonemic verbal fluency task were used to classify all bilinguals according to whether they had negative or positive mixed-language costs. Again, a main effect of language mixing was found on the Simon task in combination with a significant correlation between mixing costs and performance on the most difficult trials of that task. Surprisingly, the children who scored better on a mixed-language task obtained lower scores on the Simon task. In addition, scores on a forward translation task
correlated negatively with error rates on incongruent trials of the Simon task.

The two studies reported in this dissertation dealt with a few issues that previously remained unexplored. A first issue relates to the question whether onset age of active bilingualism interferes with the BLCE. More concretely, will language abilities have different effects in early and late bilinguals? In the study with young adults, two groups of simultaneous and sequential bilinguals were recruited. Simultaneous bilinguals had started acquisition of both languages in a home context from birth onwards; sequential bilinguals had started learning their second language at school around age eight. While mixing proficiency had a significant impact on Simon task performance, no similar effect was detected according to the participants’ age of acquisition. It was concluded that onset age of active bilingualism does not have an impact on the language control effect on cognitive control. The same was true in the study with bilingual children. No differences were found between groups of simultaneous and early sequential bilingual children.

Developmental aspects of cognitive control in bilinguals were assessed in a longitudinal study in which children were examined at two different points in time. Two groups of simultaneous and sequential bilinguals were compared to a group of monolingual controls. While no differences between the groups were found on two separate time points of a longitudinal study, (a nearly significant) between-group effect was detected in the developmental changes over two years. All children showed huge behavioural gains between ages nine and eleven, but this progress was more outspoken for monolinguals than for the two bilingual groups, who did not differ from each other.

How do these results contribute to current discussions on the cognitive control advantages in bilinguals? The data show that monolingual children catch up with their (simultaneous) bilingual peers between the ages of eight and ten. Whereas their response latencies are slightly slower around age eight, they are nearly the same two years later. Importantly, on neither of these points in time do the monolinguals score (significantly) worse than the simultaneous bilinguals. This validates the idea that bilingual advantages in cognitive control manifest themselves most prominently at
both extremes of life but not when someone is at the peak of the attentional abilities.

A second important developmental aspect that came out of this dissertation was a crucial distinction between children and adults in the direction of the language control effect. As could be expected, a direct link between language and cognitive control was observed in bilingual young adults. This means that individuals with good language control abilities were also better than others with less well developed controlled processing. In children, the effect went in the opposite direction. High-proficient language mixers were disadvantaged instead of advantaged on conflict processing. This pattern was confirmed by correlation analyses. Adults who were more proficient in switching from their first to their second language, as indicated by negative forward switching costs, also scored better on the Simon task. In children, on the other hand, forward translation proficiency correlated negatively with accuracy on incongruent trials of the Simon task.

How can this counterintuitive finding be explained? Children who obtain lower scores on a mixed-language than on a single-language verbal fluency task may apply more inhibition to the other-language lexical items than children with a negative dual-language cost. Similarly, children who inhibit other-language items more will be less proficient in translation. The critical point here is that exactly these inhibitory skills that lead to lower language control abilities are required for correct execution of the Simon task. Hence, low mixed-language proficiency as a consequence of too much inhibition may be associated with faster performance on incongruent trials of the Simon task. Whereas improved inhibitory skills lead to more inhibition and more effortful mixed-language processing in children, it is possible that young adults have learnt to use these skills in an efficient way so that they can switch more smoothly between their two languages.

Finally, our results lead to the hypothesis that monitoring rather than inhibition is the cognitive control component most affected by language control abilities. Main language control effects in children and young adults were found both on congruent and incongruent trials. Moreover, there was a trend towards a language control effect on congruence switching, both in children and young adults.
4 A sociolinguistic theory of individual variability in bilinguals' controlled processing

One way to explain the finding that language control skills are associated with domain-general monitoring processes is by attributing them to a shared genetic factor that modulates both types of controlled processing (e.g., Friedman et al., 2008). At first glance, this idea seems to be supported by the absence of age of acquisition effects on cognitive control. The reasoning goes as follows: if language control abilities are the result of experience, then why do simultaneous bilinguals not show higher mixed-language proficiency and related cognitive advantages? The sociolinguistic part of the proposed theory answers this question by arguing that not the length of bilingual exposure but the sociolinguistic environment in which an individual attains bilingualism and uses his or her languages will contribute to the development of language and cognitive control advantages.

Costa et al. (2009) was the first to explore the effects of different sociolinguistic environments on bilingual advantages in inhibition and monitoring. In order to explain why bilingual advantages were reliably found in Catalonia, Spain, but not in other regions, such as Ontario, Canada (compare Bialystok et al., 2004 and Morton & Harper, 2007), three sociolinguistic factors were isolated that could have an impact on the need for controlled processing. These factors were the power relationships between the two languages involved, the degree of bilingualism in society and the typological relatedness of the languages.

<table>
<thead>
<tr>
<th></th>
<th>Barcelona, Spain</th>
<th>Canada</th>
<th>Brussels Region, Belgium</th>
</tr>
</thead>
<tbody>
<tr>
<td>(classical) diglossia</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>degree of bilingualism</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>structural similarity</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>presence bilingual advantage</td>
<td>always</td>
<td>sometimes</td>
<td>sometimes</td>
</tr>
</tbody>
</table>

Table 4.3 Sociolinguistic factors that determine the presence of bilingual advantages in cognitive control.
Costa et al. (2009) predicted that bilingual individuals in societies with huge power differences between the languages will have a lower probability of showing bilingual advantages. Diglossic societies may serve as a good example. First described in 1958, diglossia refers to a situation in which two closely related languages are used by a single language community (Ferguson, 1958). Typically, diglossia is characterized by functional distribution, which means that each of the languages fulfills different roles. Logically, there is little need for language control when languages are strictly kept separate and fulfill distinct roles. The degree of bilingualism is another variable that might have an impact on the bilingual advantage. Naturally, the chance of an individual to be able to engage in bilingual conversations will be higher if a high number of people can understand and produce these languages. Finally, bilingual advantages might even be more frequent when the two languages are related because of the high number of cognates and similar grammatical structures.

Catalonia meets all three criteria. The Catalan region is no diglossic environment because both Spanish and Catalan have a high status and they are used in formal and informal settings. The city of Barcelona shows a high degree of bilingualism: almost 80% of all people can use and understand both languages (Vila i Moreno et al., 2004). Finally, Spanish and Catalan are related languages; they both belong to the Western Romance languages of the Indo-European language family. Hence, comparing a bilingual sample from this sociolinguistic environment with matched monolinguals will often lead to bilingual advantages in controlled processing. Crucially, it is not the genetic makeup of the Catalan bilingual that induces advantages in controlled processing, but the sociolinguistic environment in which he or she was raised.

Based on these three sociolinguistic criteria, predictions can be made on the likelihood of bilingual advantages in various sociolinguistic environments (see Table 4.3). All studies reported in this dissertation were carried out with Dutch-French bilinguals from the Brussels Region. In comparison to Barcelona, Brussels has a low degree of individual Dutch-French bilingualism. Whereas code-switching used to be norm in Brussels, nowadays only 23% of Brusselsers indicates good language proficiency in Dutch (Janssens, 2013; Treffers-Daller, 1992). Besides, both languages are not structurally related. This implies that the chance of conducting mixed-
language conversations is lower in Brussels than in Barcelona. Consequently, the likelihood of bilingual advantages in controlled processing will also be more modest. Indeed, bilingual children from Brussels did not obtain better scores on cognitive control than monolinguals. Similar criteria also apply to the Canadian context, which might be responsible for the contradictory findings in different studies (Bialystok et al., 2004; Morton & Harper, 2007).

It needs to be stressed that these sociolinguistic criteria not only are expected to explain differences in bilingual performance on cognitive control tasks, but they also determine the need for developing language control abilities. It will be argued in the following paragraphs that interfering sociolinguistic variables might explain the variability of language control abilities in studies that have shown an impact of language control abilities on general cognitive control tasks (see Table 4.4).

<table>
<thead>
<tr>
<th>STUDY</th>
<th>POPULATION</th>
<th>INTERFERING LANGUAGE SOCIOLOGICAL VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Festman et al. (2010); Festman and Münte (2012)</td>
<td>Russian-German late bilinguals</td>
<td>Language use with siblings &amp; other relatives; L2 reading &amp; writing skills</td>
</tr>
<tr>
<td>Rodriguez-Fornells et al. (2011)</td>
<td>Catalan-Spanish early and late bilinguals</td>
<td>Balanced bilingualism</td>
</tr>
</tbody>
</table>

*Table 4.4 Interfering social variables in studies that have shown an impact of language control abilities on cognitive control tasks.*

Festman et al. (2010) and Festman and Münte (2012) found that language control abilities as measured by the ability to resist interference from the non-target language predicted scores on cognitive control tasks. Participants were late Russia-born learners of German. The group of poor language controllers with low resistance to non-target language interference scored significantly lower on cognitive control than the group of proficient language controllers. Two confounding variables were reported: the language use with siblings and other relatives and L2 (German) reading and writing skills. Individuals with low language control abilities had lower L2 literacy skills and spoke more Russian than German to their relatives.
These interfering variables can easily be related to the sociolinguistic criteria mentioned above. It was predicted that the bilingual advantage would not manifest itself in populations with a clear-cut functional distribution of the two languages, because this would keep these bilinguals from engaging in bilingual (dual-language) conversations (Costa et al., 2009). Indeed, the German-Russian bilinguals who preferred Russian at home but German in other settings did show lower language control abilities than those individuals who used both languages at home. These language control abilities were directly associated with cognitive control performance, which shows how sociolinguistic environments may impact controlled cognitive processing.

Prior & Gollan (2011) found a direct relationship between language switching frequency and task switching costs: better language switchers with small language switch costs also had smaller switch costs on a non-linguistic task switching paradigm. Participants were Mandarin-English and Spanish-English bilinguals who lived in South California, USA. The two groups of good and bad language switchers thus not only differed in language switching skills, but also in language background and language sociological environment. In addition, scores on native-language (L1) proficiency were significantly different with lower scores for the Chinese-born group on Mandarin fluency than for Spanish-born bilinguals on Spanish fluency. Correlation analyses revealed that lower costs in language and cognitive switching tasks could be explained by differences in proficiency levels between L1 and L2 in the Mandarin-English bilinguals.

The confounding variable of other-language fluency was connected to the sociolinguistic environment of South California (Prior & Gollan, 2011). Due to the proximity of Mexico and the high influx of Mexican immigrants, Spanish is more readily accessible in California than Mandarin; hence, there is a higher chance for individuals to engage in bilingual conversations. Costa et al. (2009) predicted that this factor raises the need for language control and leads to bilingual advantages; this prediction was confirmed by the lower switching costs in Spanish-English bilinguals. Moreover, this study shows that sociolinguistic variables might overrule the effects from socioeconomic status. While Mandarin-English bilinguals reported higher levels of parental education than the Spanish-English bilinguals, the latter group still showed better control abilities.
In a third study that tried to link language to cognitive control in Spanish-Catalan balanced and unbalanced bilinguals, an interesting correlation was found between self-assessment of unintentional switching and response times on a cognitive control task. Thus, an individual who mixes languages unintentionally or without a clear communicative purpose was found to be slower on a non-verbal task that taps into controlled inhibition. Though unintentional switching might be the consequence of genetic variation between bilingual individuals, also experience-induced differences were found on this variable. Most notably the unbalanced bilinguals showed a tendency towards more unintentional switches. It is logical to assume that balanced bilingualism or the simultaneous acquisition of two languages early in life raises the awareness of language switches and, as a result, leads to advantages in the domains of language and cognitive control.

The combined socio- and psycholinguistic theory of controlled processing in bilinguals predicts that just being a bilingual speaker does not necessarily entail bilingual advantages. According to this theoretical framework, it is no surprise that recent studies report the absence of coherent evidence for a bilingual advantage in controlled processing (Paap & Greenberg, 2013). Much more important than just the fact of being a bilingual is the sociolinguistic environment in which an individual achieves these bilingual skills. A language context with no functional distribution between the languages, with a high degree of individual bilingualism and a structural relatedness between the two languages will more easily lead to enhanced cognitive control abilities. These cognitive advantages are mediated by higher language control abilities.

5 Future directions

5.1 The use of measures of language control in bilinguals

This dissertation used two measures of mixed-language processing to demonstrate the overlap between language and cognitive control in the bilingual brain. Two of these measures were associated to behavioural facilitation in high-proficient language mixers, which means that those
conditions that required more language control were processed faster or more accurate. In a mixed-language verbal fluency task, high-proficient language mixers actually produced more words when they had to switch between two languages than when words has to be produced in one language only. In a mixed-language semantic categorization task, these proficient language controllers were faster on L2 switch trials than on L2 repeat trials, which is indicative of a negative forward switch cost. The hypothesis was put forward that measures with behavioural facilitation would show an effect on cognitive control. Indeed, both the mixing and forward switch costs were correlated to indices of cognitive control performance.

Models into bilingual mixed-language processing have been using interference tasks to establish that non-target language word readings interfere with target language processing (see, for an overview, van Heuven & Dijkstra, 1998). These tasks are composed of stimuli with specific features that are shared by several language systems. Depending on whether these stimuli are mapped to the same response (e.g., cognates) or to different responses (e.g., interlingual homographs) in each of the languages involved, they may facilitate or inhibit linguistic processing in bilinguals. Most of these studies have not taken into account the individual variability within bilingual populations on these effects. The question may be raised if variation in interference suppression, e.g., in interlingual homographs, or in cognate facilitation might correlate with cognitive control performance. Future studies could try to design measures of language control that isolate relevant components of controlled processing, such as monitoring, switching and inhibition (Paap & Greenberg, 2013).

5.2 Measures of language control in monolinguals

Controlled language processing is not restricted to bilingual language activities. Monolinguals also need controlled inhibition to deactivate non-target lexical items such as synonyms, they have to switch between different registers of the same language, and they may need to monitor the communication environment for subtle signals of sarcasm, turn-taking etc. High language control abilities in monolinguals may thus also be responsible for the absence of bilingual advantages in some studies. Therefore, any future study that compares bilingual to monolingual
cognitive control performance should include a measure of language control that can be administered to all participants.

All measures of language control that were used in this dissertation contained stimuli in two languages and were thus not suited for use with monolinguals. Also tasks with single-language stimuli may require language control, such as when they require the processing of word sets with a different meaning but the same pronunciation (homophones) or the same spelling (homographs). Evidently, a control mechanism is needed to inhibit the non-target meaning and to activate the target meaning. This is related to what bilinguals have to do when they inhibit non-target language readings of target words or when they switch from one language to another. Recent studies have shown that many different factors may contribute to the processing speed of these words as compared to control words (e.g., Hino, Kusunose, Lupker, & Jared, 2012). Future studies can explore whether similar correlations in monolinguals can be found between language and cognitive control as in bilinguals.

### 5.3 Tracking the development of language control abilities

This dissertation has shown that language control abilities have a different impact on controlled cognitive processing in children and adults. While improved mixed-language proficiency positively correlates with the efficiency of Simon task processing in young adults, these two variables are negatively correlated in children. If it is assumed that Simon task performance is determined by the efficiency of controlled processing, its relationship with language control abilities is different for children and adults. While more controlled processing has a negative impact on mixed-language performance in children, it has a positive influence on these skills in adults. Automaticity in mixed-language proficiency might play an important role in this. Further studies could explore at what age this switch occurs.

### 5.4 Mixed-language sociolinguistic environments and cognitive control

The combined psycho- and sociolinguistic theory of controlled processing in bilinguals predicts an impact of language sociological factors on the
development of cognitive control skills. Sociolinguistic environments with a high frequency of language switching (Prior & Gollan, 2011), no functional distribution between the languages, high levels of individual bilingualism (Costa et al., 2009), and a high number of mixed-language home settings (Festman et al., 2010; Rodriguez-Fornells et al., 2011) will show cognitive advantages for bilinguals. A common point of all these environments is the presence of mixed-language interactions. A higher chance of mixed-language settings will logically result in improved mixed-language abilities. On the contrary, environments with a compartmentalization of different languages into distinct functions, as is the case in diglossic contexts, are not expected to contribute to the development of cognitive control.

Future studies can further investigate to what extent mixed-language interactions modulate cognitive control abilities in bilinguals. A very interesting hypothesis is that mixed-language educational methods might enhance controlled processing. One example of such a method is content and language integrated learning (CLIL) in which the curriculum is taught in more than one vehicular language. This form of education has been shown to have a beneficial influence on the cognitive development of children (Jäppinen, 2005; Van de Craen, Ceuleers, & Mondt, 2007). The mechanisms behind this advantage are poorly understood. It is possible that these positive results are mediated by improved mixed-language abilities as a consequence of an enriched language environment.

5.5 Neurostructural correlates of the language control network

The results of two studies reported in this dissertation show that specific forms of bilingual development have an impact on the strength of the connections between language-relevant cortical regions. Bilingualism indeed creates an enriched environment which stimulates the development of strong white matter pathways that underlie efficient communication between neurons. One component of the neural language control network, the ACC, has recently been reported to be tuned by bilingualism (Abutalebi et al., 2012). Controlled processing is possibly one of the functional demands related to bilingualism that creates structural changes in neural regions that subserve this skill.
Interestingly, one of the tracks affected by bilingualism is the left inferior frontal-occipital fasciculus. Multilinguals had higher white matter integrity in this region than sequential bilinguals and monolinguals. This bundle of fibres connects the visual cortex in the back of the brain with the dorsolateral PFC, which is one of the regions involved in the neural language control network (Abutalebi & Green, 2007). Future studies could further investigate the intricate relationship between brain structure, function and behavior in order to achieve a better understanding on how speaking more than one language creates an enriched environment that induces both functional and structural plasticity in the brain.
List of references


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