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Language representation and control in early and late bilinguals: behavioral, morphometric and functional imaging studies

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Résumé

On estime que plus de la moitié de population mondiale sait parler au moins deux langues et que 40% de cette population bilingue utilise les deux langues au quotidien. Les psycholinguistes et les neuropsycholinguistes se sont rapidement intéressés au fonctionnement du cerveau bilingue et à la façon dont deux langues pouvaient partager un seul cerveau. Ainsi, de nombreuses recherches ont porté sur la représentation de plusieurs langues dans le cerveau ainsi que sur les mécanismes permettant de passer d'une langue à l'autre, mais aussi sur la période développementale sensible à l'apprentissage des langues.

Dans ce travail, nous nous sommes intéressés au rôle de l'âge d'acquisition et du niveau de compétence des deux langues sur a) la représentation des substrats cérébraux, b) la capacité d'alterner entre les deux langues et c) la plasticité cérébrale. Pour cela nous comparons des locuteurs bilingues précoces -qui ont appris les deux langues avant 3 ans- et des locuteurs bilingues tardifs -qui ont appris la deuxième langue après 10 ans- tous ayant atteint un très bon niveau de compétence dans les deux langues. Le niveau langagier et le fonctionnement exécutif des participants ont été mesurés à l'aide de plusieurs tâches linguistiques et non linguistiques. Grâce à la technique d'imagerie par résonances magnétiques fonctionnelles (IRMf), nous avons pu identifier les substrats neuronaux des deux langues pour chacun des groupes, les aires impliquées dans le contrôle des langues ainsi que les changements cérébraux dus à l'apprentissage précoce de deux langues.

De manière générale, les résultats montrent que la compétence langagière, plutôt que l'âge d'acquisition, aurait un rôle essentiel sur la représentation des langues. En revanche, l'âge d'acquisition serait déterminant en ce qui concerne la structure cérébrale des certaines aires impliquées dans les processus langagiers.

Mots clés : Bilinguisme, Contrôle des langues, Fonctions exécutives, Plasticité cérébrale, IRMf

Abstract

It is estimated that more than half of the world's population speaks two languages and that 40% of the population uses both languages on a daily basis. Psycholinguists and neuropsycholinguists became interested early in the way in which two languages could share a single brain. They have therefore been interested in the representation of several languages in the bilingual brain, in the sensitive period during which languages are learned and also in the mechanisms that allow bilinguals to switch from one language to another without apparent effort. In this work, we investigated the role of the age of acquisition and proficiency of languages and the influence of two languages a) on the representation of cerebral substrates of two languages, b) on the mechanisms of language control and, c) on the cerebral plasticity. For this purpose, we compare early bilingual speakers, who learned both languages before the age of 3 years, and late bilingual speakers who learned the second language after 10 years, both of whom had a very good level of proficiency in both languages. Participants were assessed in a wide range of linguistic and non-linguistic tasks to measure language level and executive functioning. Using the functional magnetic resonance imaging technique, we were able to identify the neuronal substrates of the two languages for each group and the areas involved in language control, as well as cerebral changes due to the early learning of two languages. In general, the results show that language proficiency, rather than the age of acquisition, has an essential role on the representation of languages, but that the age of acquisition is decisive in regards of cerebral structure of certain areas related to language.

Keywords: Bilingualism; Language control; Executive functions; Brain plasticity; fMRI

A Freddy,
il mio Grande Gigante Gentile

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INTRODUCTION

"Language is the dress of thought, " wrote Samuel Johnson in the *Lives of Poets*. Language is the means of expression for human beings and allows us to communicate, express our ideas and build our society. This process is a natural, essential and automated behaviour, yet it is very complex. In a world in which, already in 1998, it was estimated that over 50% of the world's population was bilingual (De Houwer, 1998) and, nowadays, 40% of the world population use two languages daily and bilingualism is the norm worldwide (Grosjean, 2012), it seems essential to investigate and understand the phenomenon of the cohabitation of languages both within a community and an individual.

Studies focusing on bilingual patients with language disorders revealed different patterns of recovery: selective recovery of one language, parallel recovery of both languages or pathological language mixing (Paradis, 1977). This kind of evidence led psycholinguists and neuropsycholinguists to ask themselves about the representation of several languages in a brain, the sensitive period during which it is best to learn a second language and the phenomenon of language attrition. It has been about 20 years since researchers have started to consider the issue of how bilingual individuals can juggle with two (or more) languages without apparent effort. Before imaging data was available, studies about language and bilingualism were based on patients with lesions in the brain and on behavioral data. An important limitation of this kind of studies is the use of indirect methods to study the localization of processes in the brain. They only allow us to make assumptions about the relationship between the damaged zone and the symptoms or rely on some theoretical models based on behavioral data. However, they cannot explore in real time the cerebral activity or the brain functional networks in healthy people. In the last century, thanks to a rapid advancement of neuroimaging techniques and increasingly availability, research on language and bilingualism made a great and fast progress. Nowadays, thanks to neuroimaging techniques, neuroscientists can explore brain activity of healthy individuals performing a specific task.

The first chapter focuses on the definition and characterization of bilingualism from a psycholinguistic point of view. We focus on two important characteristics, namely the age of

acquisition and the proficiency, and discuss their impact on neural organization of two languages and structural changes in the bilingual brain. This leads us to examine the issue of how bilinguals control their languages. In the second chapter we present the concept of language control and how bilingual speakers select one language or another and which brain regions are involved in that mechanism. The third chapter turns the focus of attention to the question over the existence of bilingual advantages. Afterwards, we detail the goals of this study and, in chapter 4, the methods used in order to answer our research questions. We expose our results in chapter 5 and discuss them in chapter 6. Finally, we will present some research conclusions and perspectives.

CHAPTER 1: THE BILINGUAL BRAIN

1 A characterization of a bilingual speaker

In the bilingual literature, we cannot find a worldwide accepted definition of what a bilingual person is. This problem is probably due to the rich variety among bilingual individuals. Even if bilinguals are a landslide majority of the population (Grosjean, 1982), a lot of people think they are not bilingual because of some ancient convictions. On the one hand, because many people consider a dialect or a minority language not a real language, speakers of these kinds of languages do not consider themselves to be *a real bilingual*. On the other hand, other popular beliefs consider that, to be a bilingual speaker, it is necessary to learn a language from childhood, have perfect mastery of all languages and good skills in translation or, have no foreign accent. But as Haugen (1969: 8) says "*is it possible to keep the patterns of two (or more) languages absolutely pure […]? On the face of it, one is inclined to say no*" and this statement is sustained by the holistic view suggested by Grosjean (1989: 6) which claims that "*bilingual is an integrated whole which cannot easily be decomposed into separate parts*" and he suggests that native-like proficiency in two languages is quite rare.

So what is a bilingual? Wei (2000: 27) affirms that it "*is either arbitrary or impossible to determine*" where the boundary between a bilingual and a speaker of a second language is. Mohanty (1994: 13) gives a psycholinguistic definition that takes into consideration the heterogeneity of the bilingual speaker:

> *"bilingual persons or communities are those with an ability to meet the communicative demands of the self and society in their normal functioning in two or more languages in their interaction with the other speakers of any or all of these languages, and they rarely can speak two languages at a native-like level but rather they develop unique language behaviors".*

Hence, as Weir and colleagues (2000) point out, a bilingual speaker uses different languages for different purposes, in different contexts, with various degrees of proficiency.

It seems to be clear that the difficulty of defining bilingual resides in the complexity of the threshold of *bilinguality*. Bilinguals can vary at the degree of bilingualism and this entails a necessity of taking into account when and how did the individual learned the second language (L2), how fluent and proficient the subject is and what the function or usage is of any language he knows when studying bilingual speakers.

Considering the mentioned factors, we give a shorter list of terms used to identify bilingual speakers as proposed by Li Wei (2000: 6-7):

- *Early bilingual:* someone who has acquired two languages early in childhood.
- *Late bilingual:* someone who has become a bilingual later than childhood.
- *Simultaneous bilingual:* someone whose two languages are present from the onset of speech.
- *Successive bilingual:* someone whose second language is added at some stage after the first has begun to develop.
- *Balanced bilingual:* someone whose mastery of two languages is roughly equivalent.
- *Dominant bilingual:* someone with greater proficiency in one of his or her languages and who uses the dominant language significantly more than the other language(s).
- *Dormant bilingual:* someone who has immigrated to a foreign country for a considerable period of time and has little opportunity to keep the first language actively in use.
- *Recessive bilingual:* someone who begins to feel some difficulty in either understanding or expressing him or herself with ease, due to lack of use.
- *Functional bilingual:* someone who can operate in two languages with or without fluency for the task in hand.
- *Reception bilingual:* someone who understands a second language, in either its spoken or written form, or both, but does not necessarily speak or write it.

In this dissertation, only the first six definitions are relevant for our purpose. These definitions refer to the terms of age of acquisition and language proficiency and have been identified as possible determinants in the bilingual language representation. Early and late bilinguals, as well as simultaneous and successive bilinguals, oppose themselves with respect to the onset of L2 age of acquisition. In simultaneous and successive bilinguals, languages are the reference point and belonging to one or the other group depends on when the L2 is learned with respect to the first language (at the same time or not). In contrast, the terms of early and late bilingual depend on the age at which the L2 is learned and the boundary chosen beforehand (that can vary from study to study i.e. 3 or 5 years old for early bilinguals). The last two terms refer to language proficiency, the language skills attained regardless the age of

acquisition of the L2. In the next sections, we focus on these two factors (age of acquisition and language proficiency) giving a definition and explaining theirs effects on language processing.

2 Age of acquisition

Age of acquisition (AoA) and language proficiency are probably the major factors involved in L2 acquisition. The age at which we learn a skill or a concept is called age of acquisition and it affects the outcomes of the skill learnt. Generally, this factor is discussed in terms of critical or sensitive period. This hypothesis is based on the idea that the native language is acquired more easily and more efficiently than the L2 learnt in adulthood. The existence of a critical period in L2 acquisition is still an ongoing discussion (Costa & Sebastián-Gallés, 2014). In this section, we will approach the issue of acquiring a L2 in the early childhood or in adulthood and its consequences in terms of type of learning and ultimate performance. But first, it is important to discuss two different means of learning in order to understand the terms "sensible" and "critical period".

2.1 Implicit and Explicit learning

Concepts and skills learnt early in life, such as walking, and concepts or skills learnt later in life, such as chemistry, differ from one another by the way they are acquired. On the one hand, knowledge can be learned through purely bottom-up learning mechanisms, called implicit learning, during which new information is acquired naturally, automatically through exposure and without conscious operations and awareness (White, Hutka, Williams, & Moreno, 2013). It is acquired quite directly from experience and from the environment and is relatively effortless (Sun, Mathews, & Lane, 2007). On the other hand, explicit learning is characterized by top-down processes in which conscious operations take place to seek out the structure of the new information (White et al., 2013). Explicit knowledge is typically acquired through formal education and is a result of deliberate learning by focalized attention and is slower and harder. Moreover, implicit and explicit learning differ in the ease with which they can be verbalized (Sun et al., 2007). Explaining implicit knowledge is more difficult than explaining explicit knowledge. For example, it is harder to describe every specific movement you do when you walk than to explain how to cook "pasta alla carbonara". Implicit

representations are recalled quicker, on the contrary explicit representations are retrieved slowly and after a deliberate effort. Finally, implicit knowledge is generally holistic and depicted as *knowing how* while explicit knowledge is focused on individual features and described as *knowing what* (Cohen & Squire, 1980; see table1)

Table 1. Characteristics of implicit and explicit learning following Sun, Mathews, & Lane, 2007.

Characteristics	Implicit Learning	Explicit Learning
Effort	Easy	Hard
Learning	Unaware	Aware
Robustness	Error tolerant	Error intolerant
Knowledge	Difficult to verbalize	Easy to verbalize
Type of cognition	Hot (emotional)	Cool
Speed	Fast	Slow
Control	Cue-driven (unconscious)	Conscious
Solution	Heuristic	Algorithmic
Representation	Holistic	Analytic

Implicit and explicit knowledge are represented respectively in procedural memory and in declarative memory. The former is much more fundamental and pervasive, the latter is the specialized capacity of only the most evolved species (Paradis, 2004). Procedural memory subserves automatic, internalized motor and cognitive skills while declarative memory underlies any information that can be represented at the conscious level and can be divided into episodic memory and semantic memory. Procedural memory and declarative memory are different types of long-term memory and they have been dissociated experimentally in numerous tasks (Paradis, 2004). Maybe the most famous study showing this separation is the study of the patient known as H.M. After a surgery that removed part of his medial temporal lobe, hippocampus and amygdala, H.M. could still create new procedural memories and short-term memories, but he could not commit new events in his declarative memory. For example, he could still learn new motor skills, but not remember learning them (Scoville & Milner, 1957). This established the fundamental principle that memory is a distinct cerebral function, separable from other perceptual and cognitive abilities.

The distinction between implicit and explicit learning is fundamental to better understand and explain the concept of critical or sensitive period and the consequences in acquiring a language earlier or later in life.

2.2 The critical period

Critical or sensitive periods in development have often been advanced to explain age-related differences in the attainment of a number of skills (White et al., 2013). They can be defined as "*an age window during which a particular type of experience has a much more pronounced effect on the development of a behavior or ability than the same experience at other times"* (Trainor, 2005: 262). Generally, the privilege time for learning new skills is during early development. During this period there is a peak of brain plasticity that is followed by a reduced plasticity later in life. Loss of plasticity is an origin of less learning ability in several domains. Researchers observe a gradual decline in plasticity as the critical period closes and a final partially successful learning after this period (Newport, Bavelier, & Neville, 2002).

Critical or sensitive period is present in animals. For instance, AoA affects song learning in songbirds. Brainard and Doupe (2002: 351) found that "*like humans, birds must hear the sound of adults during a sensitive period, and must hear their own voice while learning to vocalize*". A lack of hearing sounds of other birds leads to abnormal songs learning achievement. Another critical period studied for a long time has been the critical period for ocular dominance after monocular deprivation. It causes a profound, permanent visual deficit in cats, dogs and monkeys (Hubel & Wiesel, 1970).

In humans, a critical period is visible in the music field and entails the limited possibility of processing or encoding musical pitch in absolute terms (Trainor, 2005). The absolute pitch is the fundamental frequency of each tone and some musicians have the ability to identify or re-create a given musical note. Researchers show that this ability is quite impossible to attain in adulthood, and adult learners cannot achieve this ability at the same level of those who manifested it earlier in life.

These AoA effects are generally considered evidence for critical or sensitive periods and they show the impact that they have on both sensory and motor systems in nonlinguistic

domains (Hernandez & Li, 2007). In the next section, we will consider the AOA effect on the acquisition of an L1 and an L2.

2.3 Age of acquisition in language

Evidence from neurolinguistic studies and patients shows the existence of a sensitive period in language acquisition. The critical hypothesis as proposed by Lenneberg (1967) affirms that first language (L1) acquisition must occur before puberty and that any language acquisition that takes place after this time-window will be qualitative different from that involved in early language acquisition: it will be slower and less successful than normal L1 learning (Snow & Hoefnagel-Höhle, 1978). Because normal L1 learning is built on implicit linguistic competence that relies on procedural memory and procedural memory is affected by age due to a gradual loss of plasticity, language learning will depend more on conscious declarative memory after about 5 years (Paradis, 2004). The limit of this period is not identical to every component of the implicit language system. For instance, infants acquire prosody first, then phonology, morphology, and finally syntax. In contrast, learning the vocabulary is conscious rather than implicit and is subserved by declarative memory. Even though this would mean that learning new words is not affected by the sensitive period, a theory of neurolinguistics development (Locke, 1997: 265-326) posits "*an optimum biological moment for the appropriate organization and use of the mental lexicon*". According to this theory a lack of input during the phase of utterance acquisition (5-20 months) can lead to difficulties in children when asked to perform analytical operations and recognize recurrent structural patterns (20-37 months). One of the most known cases of language-deprivation during childhood showing the existence of a sensitive period in L1 acquisition, is the case of Genie. Discovered after 13 years of isolation, she had language skills of a 2-years-old infant and even after language teaching, she was unable to fully acquire a language (Reynolds & Fletcher-Janzen, 2004).

An AoA effect seems to exist in word acquisition too. Evidence suggests that early learned words differ from late learned words in terms of access and processing (Carroll & White, 1973; Morrison & Ellis, 2000). Generally, early-learned words show faster response time in various tasks such as visual and auditory lexical decision, word reading, and picture naming tasks. Several models tried to explain the mechanism underlying this effect on the

basis of phonological storage (Brown & Watson, 1987), frequency of usage (Bonin, Meot, Mermillod, Ferrand, & Barry, 2009; Lewis, Gerhand, & Ellis, 2001) or semantic connections (Brysbaert, Van Wijnendaele, & De Deyne, 2000; Steyvers & Tenenbaum, 2005), for a review see Hernandez and Li (2007). Psycholinguistic and neuroimaging evidence suggest that early learned words are strongly connected to semantics and auditory word representations, whereas later learned words are built on these early learned word representations. Hence, late learned words need an additional effort to be retrieved at various levels, namely, semantic level, articulatory and motor level, and visual form level (Hernandez & Li, 2007).

A critical period hypothesis has been claimed also for L2 acquisition (Singleton, 2005). Penfield suggested that "*for the purposes of learning languages, the human brain becomes progressively stiff and rigid after the age of nine"* (Penfield & Roberts, 1959: 236) and that when acquisition has started after this age, it is difficult to attain a good result because of a decreasing cerebral plasticity as the brain matures. DeKeyser (2003) suggested that maturational constraints apply only to implicit language learning mechanisms and that a decline in language acquisition is inevitable because of the cognitive maturation. Bialystok (2002) indicates that language-learning ability continues to decline throughout life but, unlike DeKeyser, she proposes a gradual rather than sudden decline.

Behavioral studies have shown differences between early and late learners of a L2. Unlike acquisition of the mother tongue during infancy that is more likely to be implicit, adult learners of a foreign language tend to use declarative memory. In other words, late L2 learners rely on a different cognitive system than the native language due to the decline of the procedural memory (Paradis, 2004). Since late language learners of a L2, process their second language differently than their native language, a lower level of performance in many aspects of the languages is often (almost always) observed (Flege, Munro, & MacKay, 1995; Mackay & Flege, 2004). For instance, lower proficiency degree has been found in accent, production and comprehension of morphology and syntax, grammaticality judgements for morphology and syntax, and syntactic processing speed and accuracy (Newport et al., 2002). The study (Johnson & Newport, 1989) of Chinese and Korean immigrants who moved to the United States and learned English as L2 reported that there is a correlation between AoA and ultimate performance on L2 syntax and morphology. But AoA does not assure a high level of proficiency without a constant exposure. An extreme case showing that early experience with language does not guarantee the availability of the language phonology later in life is the

study that involved Koreans adoptees by French-speaking-families between the age of 3 and 9 years. The adoptees perceived Korean consonants in the same way than native French individuals previously unexposed to Korean (Pallier et al., 2003; Ventureyra, Pallier, & Yoo, 2004), indicating that no more traces of Korean were present in the Korean adoptees.

Other factors that might be predictive of the outcomes of L2 acquisition are for instance the environment, the amount of input that learners received in an immersed L2 context is greater than learners in a formal schooling environment; the motivation to pass for a native or to learn lexico-grammatical accuracy; the aptitude, as the metalinguistic awareness, or the integration with the L2 culture. These are all factors that might influence the ultimate L2 attainment (Birdsong, 2006). Several studies have reported a nativelikeness performance among L2 late learners (AoA $\geq$ 12 years). In the area of morphosyntax, nativelikeness has been observed in bilinguals with certain L1-L2 pairings (e.g., Cranshaw, 1997), with increased L2 use (e.g., Flege, Yeni-Komshian, & Liu, 1999), and with L2 dominance (e.g., Flege, MacKay, & Piske, 2002). In the area of pronunciation, those learners who are taken for natives by native judges tend to be those with high levels of L2 practice, motivation to sound like a native, and L2 phonetic training (e.g., Bongaerts, 1999). Anyway, AoA is "*reliably the strongest predictor of ultimate attainment"* (Birdsong, 2006: 12).

In sum, there is a wide agreement among researchers that late as compared to early learning of a second language is associated with lower ultimate performance (Singleton, 2003) and that is generally considered evidence for the existence of a sensible period for L2 learning. However, even if evidence on the AoA effect has been overwhelming in behavioral studies, conflicting results have been found for the neural bases of L2 age of acquisition effect (see chapter 5.2 for a review of neuroimaging studies).

3 Proficiency

When studying AoA in the L2 literature, another feature that is often examined is the attainment of L2 proficiency (Hernandez & Li, 2007). Ericsson and colleagues (1993), speaking about general expertise, point out that 10 000 hours of practice is necessary to achieve expertise and that practice without adequate feedback and information about corrective action does not lead to efficient learning. Discussed in terms of implicit and explicit learning, practice leads to the use of explicit knowledge faster and faster and replaces some

controlled processing by automatic processing. This does not mean that explicit knowledge becomes implicit competence, but rather that a shift from using explicit knowledge to using implicit competence is gradually achieved. That is, explicit knowledge of rules can exist alongside with automatic routines (Paradis, 2009) and explicit knowledge may indeed facilitate the acquisition of implicit competence (Ellis, 1994) operating as guidance for practice and as a monitor for checking the correctness of automatic output of the implicit system (Krashen, 1977).

Newport et al. (2002) define language proficiency as the control over sound systems as well as grammatical structure and, in L2 acquisition, is evaluated in reference to a standard that is embodied by monolingual native speaker control or presumed norms of the L2 (Birdsong, 2014). But Birdsong (2014:377) argued that "*a bilingual's proficiency in the dominant language cannot be expected to be identical to that of a monolingual native speaker of that language"*. This statement is in line with other researchers that argued the inappropriation to take a monolingual standard as reference of attainment when studying bilingualism, since bilinguals are not "*two monolinguals in one*" (Grosjean, 1989:3)

Studies of populations of healthy individuals show a strong relationship between the age of exposure to a language and the ultimate proficiency achieved in that language. Speakers whose exposure to a language begins during infancy or childhood show high proficiency in that language (Newport, 2003) while a disadvantage and a higher individual variation is found with increasing ages of exposure (Johnson & Newport, 1989). However, it has been found that some individuals may reach native-like proficiency (Birdsong, 1992). For instance, in the study of Marinova-Todd (2003) 3 out of 30 late learners of English as second language (AoA > 16 years) living in an English speaking country were indistinguishable from natives across all demanded tasks. And six others performed at nativelike levels in seven tasks out of nine. Several other studies have demonstrated the possible achievement of nativelike performance for late learners (Birdsong, 1992, 2003, 2005; Bongaerts, 1999; Ioup, Boustagui, El Tigi, & Moselle, 1994) and these results have been interpreted as evidence for the non-existence of the critical period for second language acquisition (Birdsong, 2005).

Evidence for the relative importance of proficiency as opposed to AoA can be found in studies with populations that are immersed in a L2 early in life. Work from Hernandez and colleagues (Hernandez, Bates, & Avila, 1996; Hernandez & Kohnert, 1999; Hernandez & Reyes, 2002; Kohnert, Hernandez, & Bates, 1998) suggests the importance of proficiency in lexical tasks when L2 acquisition occurs early in life in terms of response times. Their results

are consistent with the view that L2 AoA affects the processing of phonology, morphology and syntax more than lexical and semantic processing (Hernandez & Li, 2007).

A distinction must be made between proficiency and dominance. As mentioned above, proficiency is linked to a standard evaluation; on the contrary, dominance is something more internal to the speaker, in the sense that one language is compared with another without taking into account the level of proficiency of any language (Birdsong, 2014). Hence, language dominance refers to the availability of each language for language processing and can vary during an individual's life depending upon the circumstances (Köpke, forthc.). Even though (Gertken, 2013) showed the prevalence of L1 dominance, learning a language early does not always enroll a better performance of this language. Sometimes a shift of dominance from L1 to L2 is produced. It occurs, for instance, in children whose home language is different than the school or community language (Birdsong, 2014). Or, in long term bilingual immigrant in which an attrition (the non-pathological loss of a language or a portion of that language) of their L1 is observed (Köpke & Schmid, 2004). Harris et al. (2006: 264) affirmed that "*for immigrants with many years of immersion in their second language, the second language can come to be the most dominant language, even if it remains the less proficient language, as measured by tests of grammar and vocabulary"*, meaning that bilinguals become more efficient in L2 language processing than L1, even though some errors are still produced.

In conclusion, we have seen that findings of behavioral studies are still inconclusive as to whether proficiency or AoA determines the behavior in L2 learning. Behavioral studies have provided important support to the role of AoA, but AoA effects seem to diminish or disappear when early and late learners are equated on proficiency. In the next section, we will discuss findings yielded by neuroimaging studies.

4 Theoretical models of L2 processing

Over the past 20 years an amount of brain imaging data has been accumulated, allowing us to analyze language functions (language production, comprehension, reading, and writing) or linguistic processes (semantic, phonology, and syntax) and describe the localization of language function in the brain structure. The beginning of neurological investigations into bilingualism gives rise to the question about the representation of the bilingual’s two languages in the brain. Findings regarding the neural basis of L2 age of

acquisition have been incongruent. In the next section, we will discuss two models of bilingual brain function. The first model that will be discussed is the Declarative/Procedural model of language processing (Ullman, 2001b). It emphasizes age-related effects on the neural localization of L2 processing. In contrast, the Neural Convergence hypothesis (D. W. Green, 2003) supports a more proficiency driven and dynamic perspective on neural L2 processing.

4.1 Declarative/Procedural model of language processing (Ullman, 2001)

The declarative/procedural model posits a fundamental distinction: a mental lexicon composed of memorized words consisting of a combination of meaning and sound, and a mental grammar consisting of rules that underlie the combination of lexical forms. These two different language subsystems are tied to two separate brain subsystems of long-term memory: the declarative or explicit memory and the procedural or implicit memory (Paradis, 2009; Ullman, 2001a). This model posits that the memorization and use of lexical information relies on declarative memory. In contrast, procedural memory underlies the acquisition processes and use of grammatical knowledge. As explained in the section above, these two memory systems differ from each other in that only procedural memory is implicated in nonconscious learning, whereas only explicit knowledge can be consciously recalled.

The declarative memory system is subserved by medial temporal lobe regions including the hippocampus and parahippocampal gyrus. On the contrary, the procedural memory system is rooted in a network including frontal lobe and basal ganglia structures. Ullman, in this model, suggests a potential locus of convergence of the two memory systems: the temporo-parietal regions where consolidated knowledge of words is stored along with automatized procedures.

In other words, according to this model the vocabulary of a L1 is stored in declarative memory, whereas L1 grammar is represented as procedural memory. Concerning acquisition of a L2, this model predicts age-related effects on the neural representation of L2 processing. This means that L2 grammar, which usually is learned explicitly, will be more affected by age effects than vocabulary. This effect would be explained as a consequence of a shift in the type of memory system that underlies L2 grammar processing. L2 late learners would rely more heavily on declarative rather than procedural memory for grammatical processing. In this

view, L2 late learners would show more activity than L1 speakers in brain areas that are associated with declarative memory during tasks involving grammatical processing and rarely achieve native-like level of grammatical proficiency (Ullman, 2005).

4.2 Neural Convergence hypothesis (Green, 2003)

In contrast to the Declarative/Procedural model, the Neural Convergence hypothesis (Green, 2003b) proposes a proficiency-based framework of the neural correlates of a L2. Green suggests an adaptive vision of L2 representation in the bilingual brain. The neural convergence model proposes that L1 and L2 are both stored in a single dynamic neural language network. It states that during L2 acquisition the same neural circuits that are already in place for L1 will be used for L2 processing and as L2 proficiency increases, the neural representations of L1 and L2 will converge. Consequently, if Broca's area has learned to compute grammatical processing of L1, it will perform the same kind of computation for L2. This model gives little information about what neural regions will show variability between low and high proficient languages, but introduces the concept of language control. A different processing of L1 and L2 would reflect an increased cognitive competition leading to a greater demand of language control process. Abutalebi (2008) improves this model suggesting the prefrontal cortex as a possible area for the representation of low-proficient languages in the bilingual brain. A greater activity in this area would indicate the higher cognitive effort needed in processing the less proficient language. Indeed, the prefrontal cortex is a region involved in general cognitive control and in the case of language control, activation of this region indicates a need of more controlled language processing that is typical of less proficient language; on the contrary, a proficient language will be execute by an automatic language processing. In sum, according to this model the level of attained L2 proficiency, and not the AoA, is believed to determine the neural representation of the L2.

5 Neural evidence of language processing

In this section, we discuss the representation of language in a monolingual and bilingual brain. Recent neurocognitive research has increased the available evidence of neural representation of language considerably. First, this section discusses the earliest evidence of language representation in a monolingual brain provided by clinical cases. Then, we discuss recent evidence provided by neuroimaging techniques providing the time course of component processes of word production and specific brain regions during word production explained in the model of Indefrey and Levelt (Indefrey, 2011; Indefrey & Levelt, 2004). Finally, we report evidence of the representation of languages in the bilingual brain discussed with regard to the models of the L2 processing described above.

5.1 Monolingual word production

Speaking is one of the most useful skills of the human being (Costa, 2006). We learn it without manifest effort, and children at the age of 5 can already express their thoughts through complex sentences. As adults, we use this ability on a daily basis and in a quite automatic way while mechanisms and representations involved in speech production are large in number and complex (Costa, 2004).

A previous source of evidence for localization of language function in the brain comes from pathological cases. Clinical studies noted an association between damage to specific regions of the left hemisphere and deficits in specific components of language. Seminal work by pioneers such as Paul Broca and Karl Wernicke tried to establish a structure-function relationship. Nowadays, the aphasia model is far from being adequate, but some of the first lesion-related findings have never been totally invalidated, namely the involvement of Broca's area (the left posterior inferior frontal gyrus) in speech production and Wernicke's area (the left superior temporal gyrus) in auditory verbal comprehension (Démonet, Theirry, & Cardebat, 2005). However, some recent evidence has challenged the crucial importance of Broca's area. At first, a neuroimaging re-examination of Broca's patient brains revealed that lesions were not limited to Broca's area (Dronkers, Plaisant, Iba-Zizen, & Cabanis, 2007). These findings suggest that productions deficits of Broca's patients were maybe not only a consequence of damage in the frontal lobe. Another clinical study showed that speaking

without Broca's area was possible. A patient, whom the left inferior frontal gyrus (IFG) damaged after a tumor resection, reported minor deficits in speech production related to syntax complexity (Plaza, Gatignol, Leroy, & Duffau, 2009). Moreover, experimental studies did not find activity in the IFG during speech output (e.g., Etard et al., 2000; Wise, Greene, Buchel, & Scott, 1999).

The lesion deficit approach can indicate whether a cortical region is necessary for performance on a specific task but has certain limitations. This approach cannot distinguish whether a cognitive deficit reflects damage to a specialized neural mechanism at the site of the lesion or to a distributed network whose connections pass through the lesion site (Green & Price, 2001) and cannot indicate the full set of regions necessary for task performance. The neuroimaging experiments surpass the static clinical anatomic paradigm with a more dynamic method based on the recording changes in indices of cerebral activity (Démonet et al., 2005). In other words, neuroimaging techniques are supposed to determine which areas of the brain are activated during the performance of a particular task. Up until now, an abundance of data has been collected through neuroimaging studies focused on language. Production of spoken word begins with the selection of a target lexical concept and ends with the initiation of articulation. Once the selection of the conceptual message has been made, the speaker needs to "translate" the representation of the intended concept into lexical nodes (or words) and syntactic structure. Researchers have focused much more on the issue of lexical selection and less on the processing of syntactic structure. Models of speech production try to answer the question about how the speaker selects the word that corresponds to the intended message and how it is produced (e.g. Caramazza & Costa, 2000, 2001; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Levelt, Roelofs, & Meyer, 1999). Lexical selection is needed because the conceptual system activates several potential nodes that are candidates for production. These candidates are related words of the target concept. For example, in order to communicate the meaning of "cat", the conceptual system will spread activation to the lexical nodes "cat", "dog", "meow", etc. During this stage, a lexical selection mechanism assures that the word with the highest level of activation is picked out. The second main step of speech production is the phonological encoding, that is the retrieval of phonological properties of the words. All three models assume that phonological encoding comes after lexical selection, but they diverge in the extent to which phonological activation is present. The discrete model of Levelt, Roelofs and Meyer (1999) posits that phonological activation is present only after the process of lexical selection and restricted to the selected node. Instead, the so-called cascaded

models suppose that the activation of any given lexical node spreads to its phonological properties. In this view, the phonological activation is present in the system even before lexical selection has been achieved.

Starting from the theory presented in Levelt, Roelofs and Meyer (1999), Indefrey and Levelt (2004, 2011) propose a model that specifies the neural network, with regions and time windows, involved in word production (Fig. 1). They analyzed 82 experiments of the imaging literature on word production and tried to explain the successive computational stages of spoken production in terms of spatial and time course information.

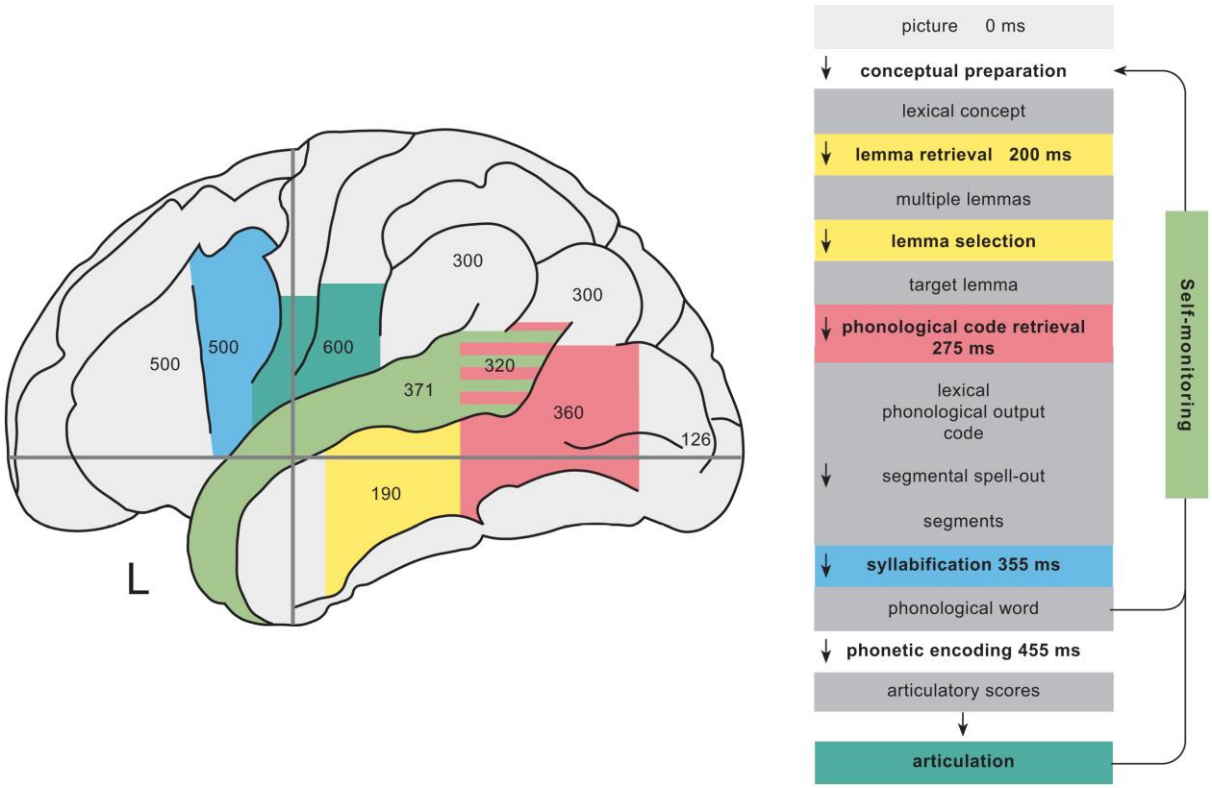

Figure 1. Schematic representation of the activation time courses of brain areas involved in word production. (Indefrey, 2011)

Schematic representation of activation time courses of brain areas involved in word production (left); the numbers indicates median peak activation time estimates (in ms) after picture onset in picture naming. In the right column, time course of picture naming as estimated from chronometric data. Colors indicate the relationship between regions and functional processing components.

Based on chronometric data and electrophysiological studies, they provided estimation for the duration of the different processing components in the picture naming task: conceptual

preparation (from the picture onset to selection of the target lexical concept) 175ms, lemma retrieval 75ms, phonological code retrieval 80ms, syllabification 125ms, phonetic encoding 145ms. The authors warned about a too strict interpretation of the time windows. The estimate of 600ms for the articulation was based on studies using repeated naming of the same picture. They reported naming latencies from various studies providing evidence for a range from 470ms to 2000ms in word production.

The review of brain activation studies allowed the authors to mapping the regions involved in language production. They analyzed studies using picture naming, word generation, and word or pseudoword reading tasks. The main components of this network are largely left-lateralized and different regions of activation appeared to be involved with the processing of different functional component. For instance, the conceptually driven selection of a lexical item, as in picture naming task, goes with activation in mid part of the left middle temporal gyrus. For picture naming and word generation tasks, they reported a set of regions consisted of the left posterior inferior frontal gyrus, the left mid and posterior parts of the superior temporal gyrus (STG) and middle temporal gyrus (MTG), the right mid STG, the left fusiform gyrus, the left anterior insula, the left thalamus, and the cerebellum. According to Indefrey and Levelt (2004) these regions can be assumed to sustain the core components of word production. In addition, they remarked that picture naming task and word generation task may activate quite different concepts, hence, the set above does not include regions involved in conceptual processing that need to be counted: posterior inferior parietal lobe, MTG, fusiform and parahippocampal gyri, dorsomedial prefrontal cortex, IFG, ventromedial prefrontal cortex, and posterior cingulate gyrus (Indefrey, 2011).

5.2 Bilingual word production

In this section we discuss functional neuroimaging evidence with respect to bilingual word production. Moreover, we explain these findings in light of the predictions of the two claims seen above: 1) the Declarative/procedural model that proposes age-related effects on the neural representation of the second language processing; 2) the Neural Convergence model that predicts proficiency-related changes.

The study of aphasia in persons who spoke more than one language have served as a valuable source of evidence for the comprehension of the cerebral organization and

processing of language. Fabbro and Paradis (1995) present cases of four bilingual patients with lesions delimitated to the left basal ganglia. All patients showed impairments in L1 grammar processing, while their L1 lexicon, as well as their L2 lexicon and grammar, were intact. Another case of a patient with subcortical lesion involving the left basal ganglia was reported by Aglioti and colleagues (1996). This patient reported greater impairment in the mother tongue than in the L2. Ku et al. (1996) reported the case of a bilingual Chinese-English aphasia patient who developed herpes simplex encephalitis involving the left temporal lobe. He lost the ability to speak or comprehend his L2 but preserved these abilities in his mother tongue.

Another important source of findings is neuroimaging studies. Difficulty arises when we want to compare neuroimaging studies focusing on language production given the high variability of tasks and participants. Tasks used in language production range from word repetition, picture naming, word generation, sentence generation, to cognate and noncognate naming. Moreover, participants differ greatly for exposure to a language and degree of proficiency. Finally, studies examine a specific group of bilingual (early or late), compare bilinguals to monolinguals, or compare early bilinguals to late bilinguals.

An early research (Kim, Relkin, Lee, & Hirsch, 1997) in language production compared late bilinguals to early bilinguals and showed different cortical activation in L2 production tasks. The authors found that the representation of the late L2 in Broca's area differed from the L1, and that was not the case for a second language learned early in life. On the contrary, this dissociation was not visible in Wernicke's area regardless of AoA. The authors suggested that AoA could be a determinant factor for the functional organization of language in Broca's area. Similarly, Bloch et al., (2009) observed less variation between L1 and L2 activation, in terms of number of voxel, in early bilinguals, compared to late bilinguals, performing a silent free narration task. Furthermore, Mahendra, Plante, Magloire, Milman, & Trouard (2003) found a greater total number of active voxel in the left IFG and STG in early bilinguals compared to late bilinguals during a word and sentence generation task. Different patterns of cortical activation have been found for a L1 acquired early in life as opposed to a L2 acquired later in life (Dehaene et al., 1997; Kim et al., 1997; Perani et al., 1996) but other studies, controlling for or manipulating the L2 proficiency, did not find the same conclusions (Birdsong, 2006). For instance, Chee et al. (1999) compared two groups of fluent bilinguals in an fMRI study. One group was formed by 15 Mandarin-English bilinguals that were exposed to both languages before the age of 6; in the other group, 9 bilinguals

exposed to Mandarin in infancy but English only after the age of 12. Subjects performed a cued word generation in each language. Early and late bilinguals showed overlapping activation for both languages irrespective of age of acquisition of either language. They found activations in the prefrontal (BA 44/45, 46/9), parietal (BA 7) and temporal (21/22) bilateral regions, and in the supplementary motor area.

A study on grammar and semantic judgements (Wartenburger et al., 2003) involving three groups of Italian-German bilinguals divided by age of acquisition and proficiency (early acquisition/high proficiency; late acquisition/high proficiency; late acquisition/low proficiency) showed that activation was related to AoA during L2 grammatical judgements. A greater activation for later learners, irrespective of their language proficiency, was observed in the bilateral middle and inferior frontal gyri extending to the anterior insula, and the inferior parietal lobule. On the contrary, during L2 semantic acceptability judgement task, similar activations were found for highly proficient late and early bilinguals. Within-group analyses were carried out comparing L1 processing to L2 processing. For both late bilingual groups, a greater activation in Broca's area and subcortical regions was found during the grammatical task, and a greater bilateral activation in inferior frontal areas on semantic judgement task in L2 processing than in L1 processing. On the semantic task, early bilinguals did not show any differences in L1 versus L2 processing. Taken together, results suggest that AoA could be a determinant factor for the neural representation of grammatical processing. Another study (Hernandez, Hofmann, & Kotz, 2007) exploring the role of AoA in syntactic processing in highly proficient early and late bilinguals showed an increased activity in Broca's area for irregular compared to regular items during a grammatical gender decision task. Furthermore, the activity in the prefrontal cortex was higher in the late bilingual group than in the early bilingual group. Authors suggested that an additional syntactic processing is demanded when processing irregular items in the late learned second language.

Wattendorf et al. (2012) compared early proficient multilinguals to late proficient trilinguals during a narrative task. The direct comparison between both groups revealed a higher activation of the fronto-stratial network predominantly in the left hemisphere in early trilinguals, whereas late multilinguals activated to a higher degree only the left posterior superior temporal gyrus. Furthermore, results revealed that the late acquired language (the third language) in early bilinguals was similarly affected, suggesting an important influence of language experience into adulthood.

Isel, Baumgaertner, Thrän, Meisel, & Büchel (2010) compared 10 early bilinguals with 10 late bilinguals in a word recognition task in L2 and observed different patterns of activation for the two groups. Early bilinguals showed higher activation in the left STG, the bilateral SFG and the right posterior insula, whereas late bilinguals showed higher activation in the middle portion of the left insula and the right MFG. These findings suggest that AoA affects neural representation of L2 words.

Other studies focused only on one type of bilingual speaker. Perani et al. (2003) asked early highly proficient bilinguals who have learned Catalan and Spanish before the age of 3 to perform a verbal fluency task in their L1 and L2. Both groups (Catalan or Spanish acquired first) showed more activation for the L2 than the L1 in multiple frontal areas, namely the left insula, which has frequently been implicated in articulatory processes, left Broca's area and left dorsolateral prefrontal cortex. Authors noted also that the group with Spanish as L1 showed a smaller difference between L1 and L2. They explained this evidence with the fact that they also had more equal exposure to the two languages. This suggests that even after a long period of exposure to L2, differences in L1 and L2 processing still remain.

Hernandez et al. (2000) asked Spanish-English bilinguals to name pictures in both languages. Participants to this study had been exposed to both languages more or less from birth, but had been educated in English and had better performance on the naming task in English. Nevertheless, fMRI results showed increased activation in the left dorsolateral prefrontal area during English naming than Spanish naming that has been interpreted as a need for more effort for English processing. Even though behavioral results indicated that English was the language they had more exposure in, at least in the years immediately preceding the experiment, Stowe and Sabourin (2005) explained these results in terms of early exposure. As participants had been exposed more to Spanish in their earliest years, it is suggested that early exposure is necessary for the most efficient use of the language areas and cannot be compensated for by later proficiency.

Vingerhoets et al. (2003) investigated language representation in 12 late multilingual speakers performing a word fluency task, a picture naming task, a comprehension task in three languages (Dutch, French, and English) during an fMRI scan. All language tasks showed predominantly overlapping regions of activation for all languages. Task performance in foreign languages revealed a tendency toward more extensive activations of the same regions activated in L1 processing and the activation of a larger number of regions. Fluency tasks in the foreign languages recruited additional bilateral inferior frontal activation,

including Broca's area and left middle temporal gyrus; the L1 elicited additional postcentral activation. In the picture naming task additional activation of inferior-lateral and medial frontal regions predominantly on the left was found and in the native language more posterior right hemispheric activation. The authors concluded that all languages recruited the same network, but in order to perform at a comparable proficiency level, later acquired languages revealed additional activation bilaterally.

A PET study on L2 cognates (De Bleser et al., 2003), showed no difference in neural activity when producing L1 words and L2 cognates. On the contrary when producing L2 noncognates additional brain activity was found around the same areas mediating L1 word production suggesting a shared lexico-semantic system.

Pallier et al. (2003) and Ventureyra et al. (2004) found interesting evidence of language attrition (the non-pathological loss of a language or a portion of that language) of first language in native Koreans who were adopted by French-speaking families between 3 and 8 years old. Remarkably, no Koreans adoptees differed from native French speaker in terms of neural activation, even those that were adopted later at the age of 8. These data suggest that when a second language is learned as late as 8, this language does not involve different neural patterns than those involved in L1 learning. Hence, any child who experiences an exclusive L2 immersion, between 3 and 8 years, can achieve a high degree of proficiency, lose any trace of L1 phonology and use the same regions as are recruited for L1 acquisition.

Some studies have also shown the importance of language exposure. An fMRI study on two groups of early highly proficient bilinguals (Perani et al., 2003) performing a word fluency task showed less left prefrontal activation in the group with more exposition of their L2 than in the group with less exposition of their L2. It suggests that the amount of input during the earliest stages of acquisition or input over lifetime, and not just the age of acquisition, has an important role for native-like processing.

fMRI and PET allow us to find out where in the brain a particular process takes place, but they are not suitable for a fine scaled tracking of when different processes occur. In contrast, ERPs and MEG are capable to measure when a language processing takes place. *When* methods are in general in agreement with *where* method conclusions, namely L1 and L2 elicited same areas in the brain. Several ERP components are sensitive to various linguistic variables. The negative component, called N400 which is usually clear by 400 msec after a word's presentation, is sensitive to semantic variables. The P600, a positive component peaking about 600 msec after the presentation of a word is sensitive to syntactic complexity.

Ungrammatical sentences can also evoke an earlier negativity, called the LAN (left anterior negativity; Stowe and Sabourin, 2005). The general outline of response for a late acquired language and a native language is the same, even when L2 acquisition begins at age 12 or after. But L2 results seem to show subtler differences, particularly in the extent to which the ERP waveform is modulated by aspects of the input. For instance, late learners do not show the earlier negative responses to ungrammatical words in L2 processing and may frequently show delayed responses as with the P600 (Stowe & Sabourin, 2005).

To summarize, evidence suggests that a bilingual can use the same neural structures to perform identical tasks for both languages, giving support to the neural convergence theory (Abutalebi & Della Rosa, 2012). Similar activations, if not identical, of L2 and L1 underlying lexical retrieval in the same individuals were found in various studies even for languages that have different orthography, phonology, or syntax (Chee et al., 1999). But Wartenburger et al. (2003) claimed that both AoA and proficiency affect the neural correlates and it depends on the processing involved (i.e., semantical vs grammatical processing) suggesting that a purely proficiency-based account of L2 processing, as the neural convergence theory, is not adequate. On the other side, differences in L2 processing are found for low-proficient bilinguals or less exposed bilinguals. At the beginning L2 learners will struggle to retrieve L2 words resulting in a slower production (Kroll & Stewart, 1994), because neural connections between the concept, the lemma, and word form are normally still weak for a low-proficient L2. Moreover, L1-dominant lexical items can interfere with L2 production causing a need for the L2 learner to block the unwanted prepotent L1 concepts. With increasing proficiency, the between-language competition can be resolved more automatically; the selection and maintenance of the correct lexical items will become more tuned and automatic. The L2 speaker will be familiar with the task and she will process the L2 in a less controlled manner. This competition between L1 and L2 is reflected in terms of greater engagement of the left prefrontal cortex or the selective engagement of more anterior prefrontal areas located outside the classical language areas and related to cognitive control (Abutalebi & Della Rosa, 2012). This additional activity cannot be a consequence of a greater specific-language neuroanatomical representation but rather a different processing demanding more effort. In other words, late learners recruited some additional non-linguistic brain areas for a proficient language use. Once sufficient L2 proficiency is achieved, the L2 learner will be less in need of cognitive resources. We will discuss the controlled processing recruited by bilingual speakers and the prefrontal activity more extensively in the next chapter.

In conclusion, this chapter shows that either attained level of proficiency (Chee et al. 1999), the onset of age of acquisition (Bloch et al., 2009; Kim, Relkin, Lee, & Hirsch, 1997; Mahendra et al., 2003; Wartenburger et al., 2003) or the amount of exposure (Perani et al., 2003) can influence the brain representation of L2, and further studies are still needed to refine the role of these factors. The next section discusses the influence of age of acquisition and proficiency in terms of changes in the brain structure.

6 Neurostructural plasticity and AoA/proficiency

The human brain has the capacity to modify its own structures throughout an individual's lifespan. The act of learning entails a reorganization of the nervous system, in the same way a lesion in a brain can lead to loss of behavioral capacity acquired earlier. This ability, called brain plasticity, is an intrinsic propriety developed for adaptation to a changing environment (Pascual-Leone, A., Amedi, A., Fregni, F., & Merabet, 2005). For instance, a study (Maguire et al., 2000) investigating brain structure of London taxi drivers showed that taxi drivers with extensive navigation experience had larger posterior hippocampi than control subjects, a region linked to spatial representation of the environment.

Recent development of neuroimaging techniques, namely structural magnetic resonance imaging (MRI), offers a non-invasive way to measure brain structure. Some possible measures obtained by this technique are the measures of gray matter and white matter density and volume, cortical surface area, and cortical thickness (for a complete a review see Marie & Golestani, 2016).

In the domain of L2 learning, evidence shows that the neural patterns of L2 experience are often, if not always, accompanied by anatomical changes in brain structure (Li, Legault, & Litcofsky, 2014) and that bilingualism could have a protective effect on age-related cognitive decline (Alladi et al., 2013; Bialystok, 2009).

One of the first studies focusing on the brain plasticity in bilingual speakers (Mechelli et al., 2004) showed that learning a second language increases the density of the grey matter in the left inferior parietal cortex and a relationship between grey matter density and proficiency and AoA. Voxel-based morphometry (VBM) revealed greater grey-matter density in this region in bilinguals than in monolinguals. Moreover, early bilinguals (AoA: < 5 years) compared to late bilinguals (AoA: 10-15 years) had greater density in this region, and it

increased with language proficiency. The authors argued that social experience rather than genetic predisposition has a crucial role in early bilingualism. Another study (Osterhout et al., 2008) reported increasing GM density in students that enrolled in a 9 week intense course. Owing to the small sample size, they focused their analysis on the left inferior parietal region and they found a correlation between gray matter density and language learning.

Stein et al. (2012) investigated language immersion effects in brain plasticity in a group of American-born students involved in a linguistic exchange in Switzerland. Participants proceeded to two MRI-measurements, one at their arrival and the second after five months. A correlation was found between the score of L2 performance and the increased grey matter density in the left IFG.

Mårtensson et al. (2012) investigated L2 learning through intensive linguistic training. They examined Swedish military interpreters before the language courses and after 3 months. Interpreters showed a larger cortical thickness in the left inferior and middle frontal gyrus, left superior temporal gyrus and a higher hippocampal volume compared to controls. Moreover, changes in the right hippocampus and in left STG were found only in interpreters that easily achieved L2 learning, while those who struggled in L2 learning showed larger cortical thickness in the left IFG. These findings showed the influence of adult-language acquisition on structural changes in brain regions that are related to language functions.

Klein et al. (2014) examined the role of age of acquisition in second language learning in early simultaneous bilinguals (0-3 years), early sequential bilinguals (4-7 years) and late bilinguals (8-13 years) compared to monolinguals. No difference was found between monolinguals and early simultaneous bilinguals. But they observed higher thickness in the left IFG and lower thickness in the right homologue region in early sequential and late bilinguals compared to monolinguals. Moreover, they found a correlation between with AoA and the cortical thickness of the left-IFG: the later an L2 was acquired the thicker the cortex.

To summarize, findings on structural changes in L2 acquisition are still exiguous and studies differ considerably one to each other (Stein, Winkler, Kaiser, & Dierks, 2014). But still, evidence suggests that the regions most related to L2 learning seem to be left IFG and inferior parietal lobule. Both regions have been associated with L2 learning in functional neuroimaging studies too. Posterior regions seem to be related to L2 high-proficiency and frontal regions seem to be related to L2 low-proficiency in structural and functional neuroimaging studies.

Another important factor which we are interested in is the issue of language control and how a bilingual speaker manages the interaction of two languages. The next chapter discusses this mechanism.

CHAPTER 2: NEURAL CORRELATES OF LANGUAGE CONTROL IN A BILINGUAL BRAIN

1 Language selection

One of the most exquisite characteristics of bilingual speakers is their ability of alternating from one language to another without apparent effort. Bilinguals can control the mode of their bilinguality depending on the situation. It means that an individual who has access to more than one language can regulate the degree of access to her languages based on who they are speaking or listening to, the topic, the purpose of the interaction, etc. For instance, bilingual speakers can communicate in just one language and avoid interference from the non-target language during a conversation with a monolingual speaker; instead they can share their two (or more) languages and allow language mixing if communicating with other bilinguals.

An important finding in bilingual lexical access assumes that both languages of a bilingual person are always activated even if she is reading, listening or even speaking in only one of her languages (Costa, Miozzo, & Caramazza, 1999; Hermans, Bongaerts, De Bot, & Schreuder, 1998). This finding is surprising with respect to language production, since one could think that the easiest way to have no interference from the language not in use is to limit the activation of that language. Furthermore, bilinguals, once they reached higher level of L2 proficiency, rarely produce language errors during conversation (Poulisse & Bongaerts, 1994), and, if the context allows it, they can switch between languages without effort.

Along with these considerations, Grosjean (1985) puts forward a psycholinguistic model in which the various bilingual language modes can be represented by the points of a continuum: from the monolingual mode to the bilingual one.

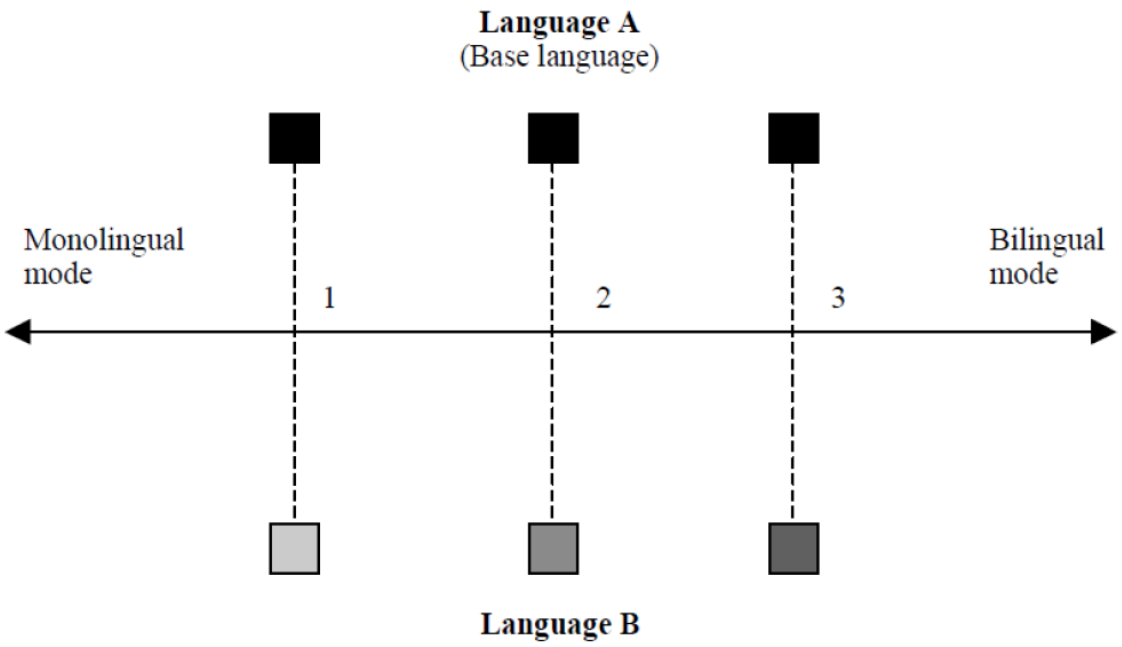

Figure 2. Visual representation of the language modes on a continuum.

Language A is the language selected as a base language by the speaker. In the monolingual mode, the language B is in "standby" which allows the speaker to avoid intrusions. In the intermediate position, language B is slightly activated which allows to use it while limiting the intrusions. In bilingual mode, it is highly activated which allows to mix the codes. The colors represent the degree to which a language is activated. Source Struys, 2013, p. 16).

Figure 2 is a visual representation of the monolingual-bilingual continuum following Grosjean (1999). At one end of the continuum (on the left), bilinguals are totally in a monolingual mode: they are communicating only with monolinguals of one of the languages they know. Therefore, one language is active and the other is only very slightly active. At the other end of the continuum (on the right), bilinguals find themselves in the bilingual language mode. In this case, they are interacting with bilingual speakers who know their two (or more) languages. The intermediate situation depends on the attained level of proficiency of the recipient and her predisposition for the bilingual mode. Usually a language (language A in the figure) is adopted as a base language of the conversation, but the other language is still available if required in the form of borrowing and code switches. A code switch is a complete shift from one language to the other for a word, a phrase or a sentence. On the other hand, a borrowing is a word or short expression taken from the less activated language and adapted morphosyntactically and sometime phonologically into the base language (Grosjean, 2006).

Since both languages are activated in bilingual mode, controlled language processing is needed to suppress unwanted interference in situations of mixing language such as

translation, interpreting or even when the bilingual speaker uses a less proficient language. A definition of language control is provided by Abutalebi et al. (2007: 1496):

> *"language selection (or control) refers to the cognitive mechanism that controls which language to use at a given moment and context".*

In other words, language control allows bilinguals to selectively speak in one target language while avoiding the interferences from the language not in use. To understand how a bilingual speaker manages to speak and understand one language at a time without (or almost without) interference of the other language, it is necessary to employ the concept of cognitive control. The next section discusses the terms of cognitive control and language control.

2 Executive functions and language control

Adaptation to a new or complex situation is managed by, so called, cognitive control. It regulates novel situations outside the domain covered by automatic processes, where routine activation of behavior would not be sufficient for optimal performance. Cognitive flexibility is involved in multiple specific controlled cognitive processes called executive functions (EF). They include inhibition of prepotent response, shifting of mental sets, planning, action selection, monitoring and updating of working memory representations, error detection, and behavioral correction. These operations require intention and awareness (Ridderinkhof, Forstmann, Wylie, Burle, & van den Wildenberg, 2011) and without them our behavior can become "*poorly controlled, disjointed and disinhibited*" (Elliot, 2003: 50).

Studying executive functions is challenging: they are an elusive concept, hard to define (Jurado & Rosselli, 2007) and to measure. Several psychological tests have been created with the aim of measuring executive functions: Stroop test (Stroop, 1935), Trail Making Test (Reitan, 1958), Wisconsin Sorting Card Test (Milner, 1963), etc. But the main reason causing the difficulty in their measurement is the *task-impurity* problem (Miyake & Friedman, 2012). It is impossible to find a task that measures only one specific executive function because each executive function must be placed in a specific task context. Thus

scores derived from that task necessarily incorporate systematic variance obtained from non EF-processes.

In the literature of cognitive control, one important question still discussed is whether the processes underlying executive functions should be conceived as a single entity or separable different components. Miyake et al. (2000) focused on the three major components of executive function: shifting between tasks of mental sets, monitoring and updating of working memory representations, and inhibition of prepotent response.

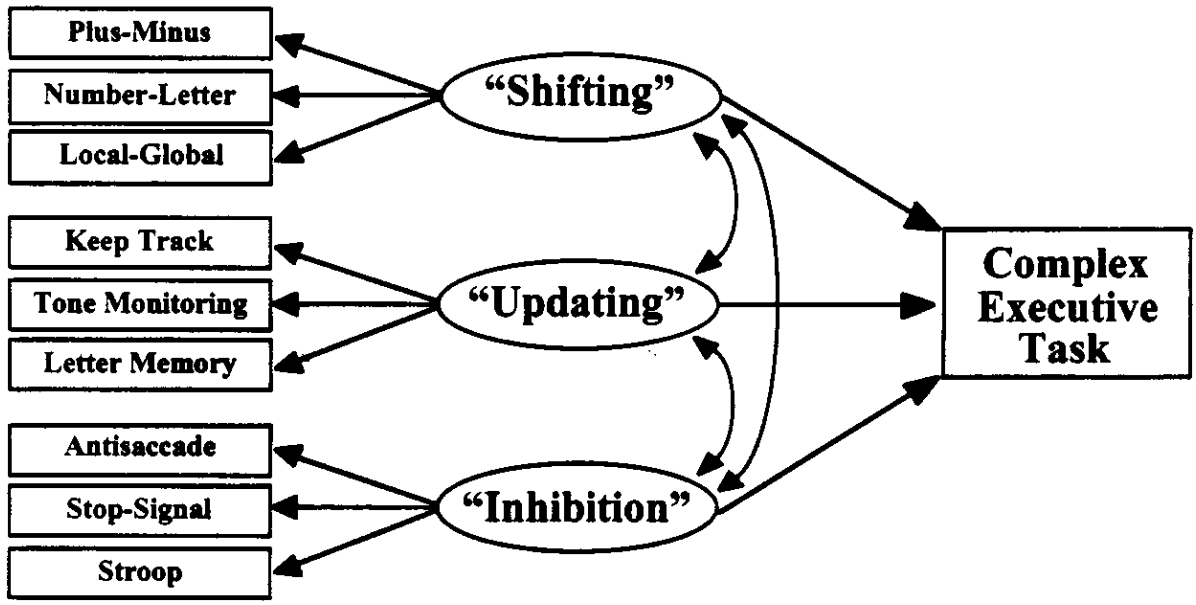

Figure 3. The three-fold structure of the model of Miyake and colleagues (2000).

A generic model for the structural equation modeling (SEM) analysis. In this model, the manifest variable on the right has paths from all three latent variables to estimate the contribution of each to performance on the executive task.

Shifting is also referred to as "attention switching" or "task switching" and is the ability to shift back and forth between multiple tasks. *Updating* concerns the transient storage of information. Any incoming information is coded and monitored to extract their relevance to the task; when newer and more relevant information come in, this will be added to the working memory and the old representations will be deleted. *Inhibition* is the ability to inhibit voluntarily dominant, automatic, or prepotent responses when needed. The aim of Miyake's study (2000) was to examine how different executive functions relate to one another. In this study, participants completed 9 tasks to examine these three abilities separately (shifting, updating and inhibition). Their findings suggest that these three components of EF are clearly separable but not completely independent, and that they may depend at least in part on some common processing resources as illustrated in the Figure 3.

Historically, executive functions have been linked to prefrontal regions due to descriptions of patients with frontal lesions (ex.: the most famous being patient Phinaeas Gage; Godefroy, Jeannerod, Allain, & Le Gall, 2008). Indeed, these patients showed impaired planning, organization, judgement and decision making (Stuss & Benson, 1984), impaired intellectual abilities and behavioral disinhibition (Luria, 1969).

Recent research suggests that not only frontal areas but larger neuronal circuits are engaged in cognitive control. Even though the prefrontal cortex is a fundamental component for executive function, other regions as posterior cortical regions and subcortical structure are involved in efficient executive processing (Collette & Salmon, 2014; Elliot, 2003). It seems that any executive task activates a common network including dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), parietal cortex, motor areas and cerebellum but also process-dependent specific regional activation (Collette & Salmon, 2014; Niendam et al., 2012).

The next section tries to elucidate regions involved specifically in language control.

3 A neural circuit of language control

Neuroimaging studies have suggested that language control involves different brain areas rather than a single region in the brain. Various neocortical and subcortical areas have been identified as participants of this neural network, namely the prefrontal cortex (PFC), the anterior cingulate cortex (ACC), the supplementary motor area (SMA), the inferior parietal cortex, the thalamus, the caudate nuclei and the putamen in the basal ganglia and the cerebellum (see Figure 4). The main function of this network is to filter out irrelevant information, to select relevant features for task performance and to inhibit prepotent non-target responses (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). We will illustrate in the next section the role of each component.

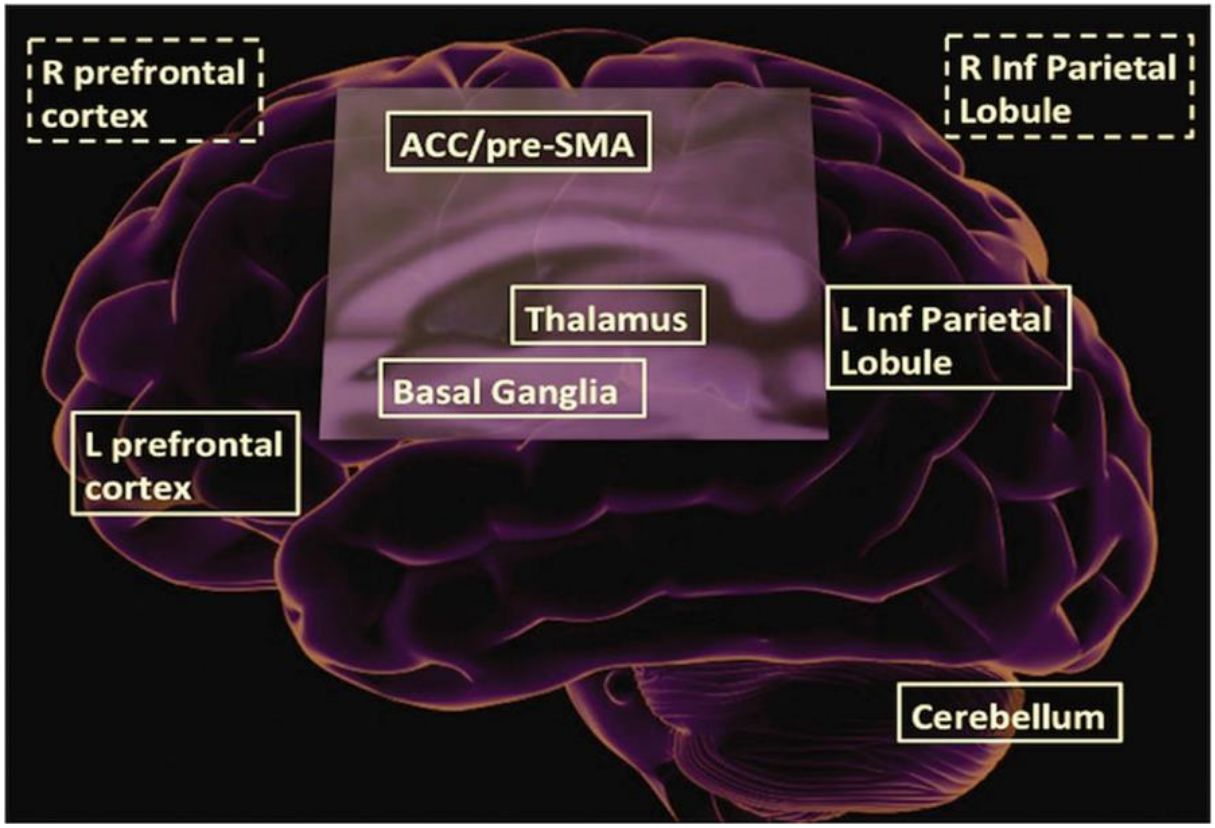

Figure 4. Model of brain regions related to language control.

This figure illustrates the components and functions of the neural language control network. Source: Abutalebi & Green, 2016)

3.1 The lateral prefrontal cortex

The main component subserving cognitive control is the prefrontal cortex (situated in the anterior part of the cerebral cortex). Since this region is largely interconnected with others areas, namely the cortical sensory systems, the motor systems, and many subcortical structures, it coordinates a wide range of cognitive processes (Miller & Cohen, 2001).

The PFC is involved in executing simple, automatic behavior (Miller & Cohen, 2001); a rapid performance of natural or well-trained behaviors without demanding much attention is possible between sensory stimuli and corresponding responses (Ridderinkhof, Van Den Wildenberg, Segalowitz, & Carter, 2004). But, when an automatic response to a stimulus need to be modified, more effort is required and in this case the PFC is crucial to processing the top-down mechanism permitting the behavioral change (Dehaene & Changeux, 1991).

Each area of PFC is presumed to be involved in specific and separable cognitive functions but the exact role of each portion is still an open field (Elliot, 2003). However, subdivision of the PFC needs to be taken into account (Ridderinkhof et al. 2004): the lateral portion seems to be involved in working memory, planning and sequencing of behavior, response inhibition, language and attention (Abutalebi & Green, 2007). According to Petrides (2005), the lateral PFC can be divided in two parts: the dorsolateral (BA 9 and 46) and the ventrolateral part (BA 45 and 47). The dorsolateral prefrontal cortex (dlPFC) seems to play a role in selecting the right task-relevant internal representations, sequential processing and self-monitoring (Ridderinkhof et al. 2004), for instance, involuntary language switching is observed while stimulating this region (Lubrano, Prod'homme, Démonet, & Köpke, 2012). On the other hand, ventrolateral PFC (vlPFC) seems to be associated to conscious retrieval of information from posterior neural regions. Moreover, Petrides' hypothesis (1999) assumes that active-controlled retrieval requires the engagement of the inferior prefrontal cortex, and the automatic retrieval does not. For instance, in word production, the processing of a low L2 may require the engagement of the inferior prefrontal cortex because the process is not automatic yet. On the contrary, processing a high proficient language, as the L1 or a well-mastered L2, does not rely on the prefrontal cortex because more automatic except for some extremely difficult tasks, as translation.

Evidence shows that right and left PFC may subserve two different cognitive processes. Left PFC has been more associated with response selection and right PFC has been related to response inhibition (Aron, Behrens, Smith, Frank, & Poldrack, 2007). Videsott et al. (2010) reported a greater activation in the right middle frontal gyrus during naming in the highly proficient languages compared to naming in the weaker languages. Moreover, they found a correlation between activity of the right dlPFC (middle frontal gyrus) and naming accuracy, suggesting that this activation can be a measure of language proficiency for fluently spoken languages.

3.2 Inferior parietal lobules

As mentioned above, the prefrontal cortex is not the only region involved in cognitive control. For instance, the neural network implicated in selection of competing responses is

also composed by the inferior parietal cortex (Abutalebi & Green, 2007; Petrides & Pandya, 1984).

The inferior parietal lobule is a portion of the parietal lobe and it is divided into two gyri: the supramarginal gyrus and the angular gyrus. The former is situated above the end of the lateral fissure, in front with the postcentral gyrus, and behind with the superior temporal gyrus; while the latter is located over the posterior end of the superior temporal sulcus, behind which it is continuous with the middle temporal gyrus. Historically, the left angular gyrus has been related to language control. Pötzl (1925) thought he had found the multilingual talent area observing patients with a lesion in that region who could not switch among their languages anymore.

The inferior parietal lobules have been reported to be engaged in attentional tasks, evaluation of conflicting choices (Rushworth, Paus, & Sipila, 2001), detection of novel stimuli (Kiehl et al., 2005) and maintaining a representation among possible responses (Bunge et al., 2002). The most inferior part (the temporo-parietal junctions) has been related to bottom-up attentional orienting (Shomstein, 2012).

In language switching context, a dissociation has been proposed between right and left inferior parietal lobule: the left inferior parietal lobule could be related to selection of the target language from the language not in use, whereas the right inferior parietal lobule could be associated with language selection towards the language in use (Abutalebi & Green, 2007).

3.3 Anterior Cingulate Cortex and pre-SMA

Anterior cingulate cortex (ACC) is the frontal part of the cingulate cortex, a medial region surrounding the anterior part of the corpus callosum. Activation in the ACC has been found in tasks that engage selective attention, working memory, language generation, and controlled information processing (Cabeza & Nyberg, 1997). Principle roles of the ACC are processing error detection and conflict resolution (Collette & Salmon, 2014). Modulating cognitive control, it performs the evaluation of cognitive control needed by signaling the occurrence of conflicts during simultaneous co-activation of incompatible responses (Abutalebi & Green, 2007; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998).

Conflict resolution, as in a Stroop task, may entail the co-activation of PFC and anterior cingulate cortex (Collette & Salmon, 2014; Massa, Cortelazzo, El Yagoubi, & Köpke, 2016) but recent neuroimaging studies have separated the role of these two regions. It seems that ACC has the function of conflict detector and it signals the consequent need of control to the prefrontal cortex that, in response, implements control by modulating the posterior cortex and the basal ganglia (Abutalebi & Green, 2007; MacDonald, Cohen, Stenger, & Carter, 2000). Another example of cognitive conflict showing the activation of the lateral parts of the PFC and the ACC in language processing is the tip-of-the-tongue (TOT) phenomenon. It refers to temporary failure to access to known information or word that one is sure to be familiar with. During a TOT state, cognitive control mechanism is recruited to resolve the conflict between the conviction of knowing the word and the failure to retrieve it (Maril, Wagner, & Schacter, 2001).

Fabbro et al. (2000) reported a case of a patient affected by pathological switching alternating his languages across different utterances but never within the same utterance. This patient had a lesion of the left anterior cingulate cortex (and partly of the right), and of the white matter in the frontal lobe. The patient did not show any aphasic symptoms but he switched between languages even though he was aware he had to use only one language.

In conflict monitoring, activation of the ACC is often found along with the pre-supplementary motor area (pre-SMA). Supplementary motor area is a medial region of the prefrontal cortex situated just anterior to the primary motor cortex. The pre-SMA has been associated also with initiating speech in language switching (Abutalebi et al., 2008; Wang, Xue, Chen, Xue, & Dong, 2007) and cross-linguistic conflict resolution (Rodriguez-Fornells et al., 2005). Activations of this complex of regions (ACC and pre-SMA) has been found in several studies, both in monolingual and bilingual speakers, when individuals must monitor correct responses in language tasks in which cognitive control was required such as switch tasks (Abutalebi & Green, 2016)

3.4 Basal ganglia and thalamus

The basal ganglia are a group of subcortical nuclei (the caudate nucleus, the putamen, and the globus pallidus) situated deep beneath the cerebral cortex and strongly connected to the cerebral cortex. They are traditionally associated with motor control. For instance, a lesion

to this region causes dysfunction of movement (Abutalebi & Green, 2007), as in patients affected by Parkinson's disease (Fabbro, 1999). But recently, they have been strongly linked to cognitive control too with one of their main functions being cognitive sequence planning (Graybiel, 2000).

Lesions to the basal ganglia are associated to pathological language production. In a case study reported by Abutalebi, Miozzo, & Cappa (2000), a polyglot patient with damage to the left caudate nucleus showed pathological language mixing. Language comprehension was intact, while her oral production was characterized by spontaneous and involuntary switching between her languages. This suggests the implication of the basal ganglia in the selection of the most appropriate lexical alternative.

Within the basal ganglia, two distinct systems specific to language use have been found. The first one associates the putamen to the motor control aspects of language; the other one relates the head of the caudate to language control. Gil Robles, Gatignol, Capelle, Mitchell, & Duffau (2005), processing a direct electrical stimulation to these two regions, found that stimulation to the putamen lead to a motor speech disorder (dysarthria or anarthria), while stimulation to the caudate nucleus provoked perseveration in picture naming.

Finally, the thalamus is a small structure situated in the forebrain, near the center of the brain. A lesion in this region can cause various language disorders: alteration in verbal expression with anomia, mild comprehension deficit, disorders in reading and writing (Fabbro, 1999). Neuroimaging studies interested in bilingual language production have related this area to selection of relevant lexical and semantic representations (Abutalebi & Green, 2016).

3.5 Cerebellum

The cerebellum, in Latin "little brain", is located in the hindbrain, between the brain and the nerve cord and it is linked to all the regions involved in language control (D. W. Green & Abutalebi, 2013). Originally, the cerebellum has been linked to motor disorders but recent research has shown the involvement of this region in several language and cognitive functions (Abutalebi & Green, 2016). Studies on patients with cerebellar disorders have revealed the presence of ataxic dysarthria in word production (Fabbro, 1999). This disorder affects motor production of speech, causing errors in articulation and phonation.

Neuroimaging studies have linked a lack of activity in this area to impaired morphosyntactic processing in bilingual speech production (Marien, Engelborghs, Fabbro, & De Deyn, 2001), however, the precise contribution to this process is still unclear.

4 Theoretical models of language control in bilinguals

When speaking, monolinguals need to retrieve the lexical item corresponding to the target concept. Most models admit that the lexical access is a competitive process in language production (Finkbeiner, Gollan, & Caramazza, 2006). The selection of the right lexical node depends on the level of the activation of this one and on the activation level of non-target competitors too. Compared to monolinguals, bilingual speakers have conceptual representations linked to two different lexical representations. For bilinguals, most of the words have an equivalent translation in the other language that can compete for selection. In this context, psycholinguistic researches have examined the issue of how the control mechanism guarantee output in the target language. Two accounts proposed a different solution for this problem. The lexical access is solved by lowering the activation of the lexical nodes in the non-target language (the Inhibitory control mechanism, D. W. Green, 1998), or the lexical competition is limited to the activation levels of lexical nodes in the target language (the language-specific selection, Costa & Caramazza, 1999). The next section discusses these two accounts.

4.1 Inhibitory Control model (Green, 1998)

One of the most influential models in the psycholinguistic literature on bilingualism is the inhibitory control (IC) model proposed by Green (1998). This model posits that language selection is achieved through an inhibitory mechanism that suppresses the activation of the non-target language. It is based on the model of attentional control by Norman & Shallice (1986) which specifies how routine and non-routine behavior are controlled and achieved by executive functions. According to this model each individual's action or thoughts is a schemata influenced by the environment. It identifies two levels of schemata. In the case of a schema under familiar situation, the cognitive control over the schemata is operated by a *contention scheduling*, while in the case of a schema under an unusual procedure the

supervisory attention system (SAS) ensures the activation of the appropriate task schema of novel situation and at the same time ensures the inhibition of the other competing schemas (Figure 5). In the context of language tasks, this model assumes that naming a word is a low-level schema whereas translation, letter writing, conversational exchange are higher-level schemas. The SAS mediates the communicative intention through the lexico-semantic system and a set of language task schemas (Green, 1998). Once a language task schema is specified by the SAS, it regulates the activation or the inhibition of the representation of the lexico-semantic system determining the output.

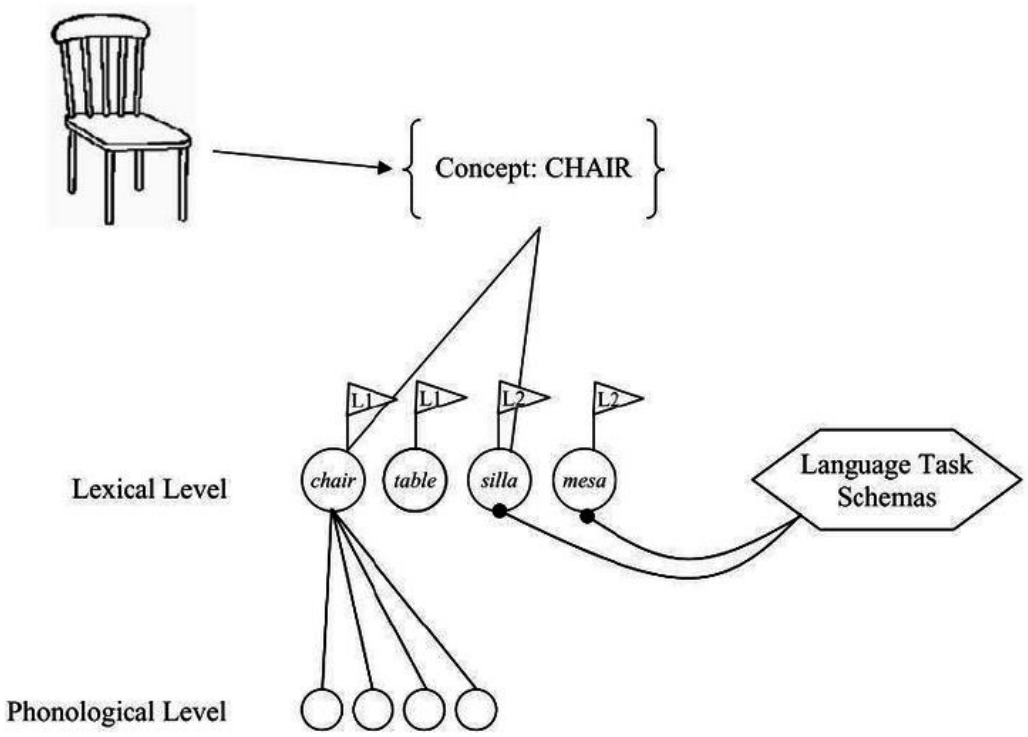

Figure 5. Inhibitory control model. Green, 1998.

A simplified version of the Inhibitory Control Model. In this example, the target language is English (the speaker's L1), and the non-target language is Spanish (L2). The inhibitory connections between the language task schemas and L2 lexical nodes indicate suppression of lexical nodes in the non-target language.

According to the IC model each lemma of the lexicon has tags that identify his language membership. A set of language schemas activate the appropriate lemmas and reactively inhibit inappropriate lemmas using language tags. This inhibition ensures the selection of the appropriate word in the appropriate language and is presumed to be reactive, meaning that effects of prior inhibition endure over time. Moreover, the extent to which inhibition is required depends on the level of activation of a particular lexical item. In this

context, the IC model predicts a switch cost between languages. This is because changing between languages entails a change of schema and requires overcoming the inhibition of the previous language tags (Green, 1998). This effect is calculated by subtracting latencies on non-switch trials from switch trials and it predicts asymmetric switch costs when switching from a low-proficient language to the more proficient one due to stronger needs of inhibition. Since the more dominant language requires more inhibition during L2-production, unbalanced bilinguals should be slower to switch into their L1 (Green, 1998).

In other words, according to this model speaking a target language is equivalent to a task schema. The selection of a specific schema over all competitors is determined by the level of activation of the schema and activation level can be determined by external inputs or by attentional and motivational components (Abutalebi & Della Rosa, 2012).

4.2 Language-specific Selection model (Costa & Caramazza, 1999)

Contrary to the IC model, Costa & Caramazza propose a model that does not assume language inhibition and control during language selection: the language-specific selection model. According to this model there is no competition between the two languages because the selection mechanism considers only the activation levels of lexical nodes of the target language (Figure 6). In other words, only lexical nodes belonging to the target language can create interferences and competitors of the language not in use are ignored. In this context, active inhibition of the non-target language is not required and the intention of using a language, specified in a preverbal message, is sufficient to ensure that words of the correct language are more activated than words of the non-target language (La Heij, 2005). Hence, in the context of language switching paradigm, longer latencies in picture naming are due to competition between lexical nodes of the language required for naming.

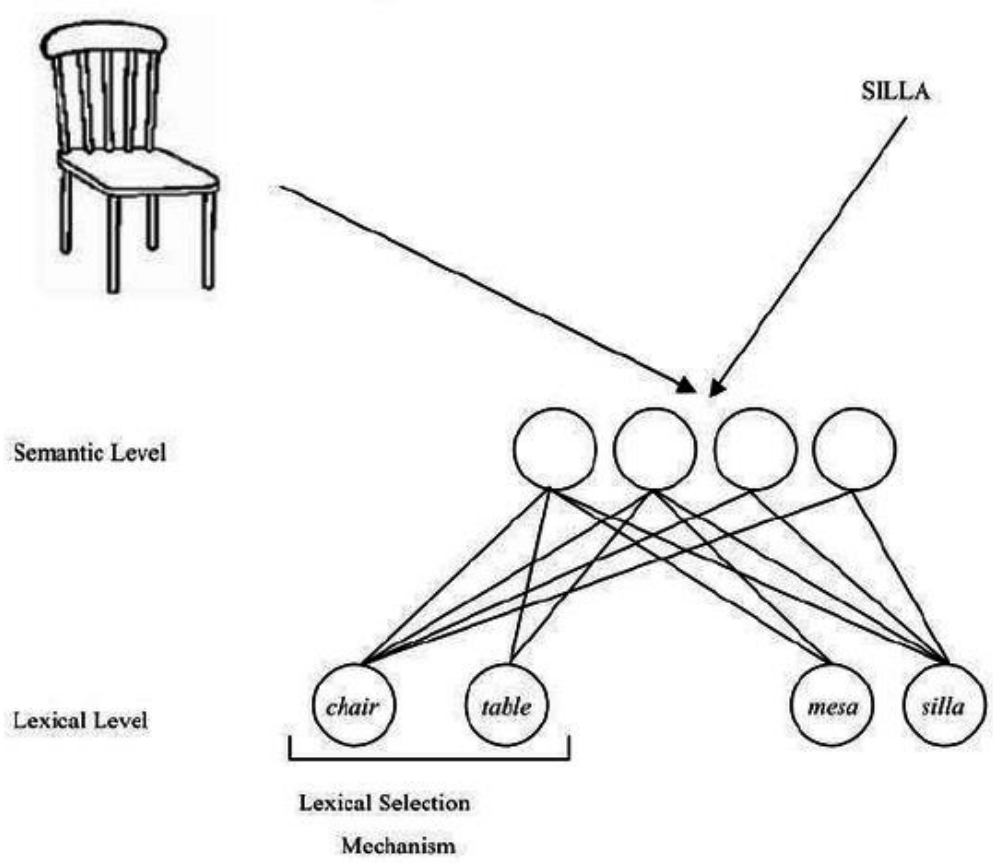

Figure 6. Language-specific Selection (Costa & Caramazza1 1999).

According to this account, the lexical selection mechanism only considers for selection lexical representations belonging to the target language. In the picture–word interference paradigm, distractor words are thought to activate semantic representations directly (via an input orthographic lexicon).

To summarize, the IC model helps to understand how controlled processing demand might influence performance on mixed-language tasks. However, in some bilinguals, language switching may be automatized and the need of more controlled processing may depend on their individual frequency of mixed-language communications. In the IC model, switch costs are linked to the idea that mixed-language use is effortful compared to single-language use. But language switching seems to be omnipresent bilingual communities (Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012) and it has been shown to be commonly present in bilingual interactions in high-proficient bilinguals (Miccio, Hammer, & Rodriguez, 2009). The IC model does not take into consideration the fact that code-switching in some cases is used as a strategy for efficient communication. Moreover, symmetrical costs have been observed in unbalanced bilinguals in a voluntary switch task (Gollan & Ferreira, 2009) and in highly proficient bilinguals when switching to a third low-proficient language (Costa, Santesteban, & Ivanova, 2006). In order to explain such results,

Costa et al. (2006) proposed a framework that supports the two models in questions. They suggested that the inhibitory mechanism is present in low proficient bilingual speakers to guarantee lexical selection in the target language, while an increase in L2 proficiency leads to a shift in the selection mechanism in favor of the language-specific selection model. This implies that once a certain level of proficiency is attained in both languages, language control mechanism does not rely on inhibition-related brain regions.

5 Evidence of language control mechanism

5.1 Behavioral evidence

Language switching paradigm and picture naming paradigm are the most suitable and used tasks to examine language switching mechanism. During these tasks, individuals name words, numbers or pictures in the same or in a different language determined by a cue. Depending on the stimuli chosen for the task two effects can be found. On the one hand, we can find what researchers call the "cognate" facilitation effect. Cognates are (quasi)-identical words that share the same meaning and similar phonological form in different languages, and naming this kind of words leads to faster response naming compared to non-cognate words (Dijkstra, Van Jaarsveld, & Ten Brinke, 1998) and also compared to monolinguals (Caramazza & Brones, 1979). A similar effect is also found in picture naming task with a translation equivalent priming (e.g. the French word "maison" (= house) with the picture of a house to be named in English). One could suppose that a similar distractor must be the strongest competitor due to the interference of the two language systems, but findings show that actually it leads to faster naming response (Abutalebi & Green, 2007). This result has been explained as a priming effect of a semantically-related word (D. W. Green, 2002).

On the other hand, it has been found that naming non-related words leads to slower response latencies when switching from the low-proficient L2 to the high-proficient L1 (Meuter & Allport, 1999; Philipp & Koch, 2006; Verhoef, Roelofs, & Chwilla, 2009). This switch cost is normally explained in terms of active inhibition (Green, 1998). The lemmas of the non-target dominant language must be strongly inhibited to avoid interference during naming in the non-dominant language, hence, as a result a larger effort is necessary to

reactivate these lemmas. Interestingly, this result has not been found when balanced bilingual speakers switch between two high-proficient languages, or between a L1 and a less proficient third language, L3 (Costa & Santesteban, 2004) suggesting the existence of a language specific mechanism. A direct evidence of the existence of this mechanism is revealed in a behavioral study of (Calabria, Hernandez, Branzi, & Costa, 2012). In this study, the authors compared the performance of a group of early highly proficient bilinguals performing two language switching tasks and two non-linguistic switching tasks. In the first experiment, bilinguals performed a picture naming task in their first and second highly proficient language and a sorting card (shape and color) task. In the second experiment, bilinguals have to name in their highly proficient L1 and low proficient L3 and the non-linguistic switching task was the same as in the first experiment. Overall, participants showed symmetrical switch costs in the language switching task, but asymmetrical switch costs in the non-linguistic switching task. The switch costs for L2 and L3 remained constant. The authors interpreted these results as evidence of a specific bilingual language control.

5.2 Neuroimaging evidence

The pioneer functional neuroimaging study involving a switching paradigm was a PET study realized by Price and colleagues (1999). They examine 6 German-English bilingual individuals during translation and language switching. The authors reported higher activity in language switching in the bilateral supramarginal gyri, regions associated with phonological processing, and the left IFG (BA 44). Translating compared to reading in different languages, activates the ACC and bilateral subcortical regions, namely the striatum, putamen and head of caudate. The authors explained this result with the need for a less automated circuit due to a greater coordination of mental operation during translation.

Two years later, Hernandez and colleagues (2001) performed an fMRI study with early Spanish-English bilinguals during a single and mixed-language production in a blocked design. The authors reported higher activity in the left dorsolateral prefrontal cortex for the switch condition compared to the non-switch condition, providing evidence that this region is involved in between-language switching. No increased activity in this region was found for within-language switching between naming verbs and nouns.

A subsequent study investigating between-language switching (Hernandez, 2009) showed higher activation not only in the prefrontal cortex but in a larger circuit involving the left superior parietal lobule, the right precentral gyrus and the right SMA. These areas have been associated with automatic language processing, and specifically to motor processing, articulation and phonological retrieval, respectively.

In the same year Wang and colleagues (2009) reported similar findings for a numeral reading task performed by Chinese-English speakers. They found higher activation in bilateral PFC (BA 46), left IFG, right cerebellum and SMA. These results are in line with the study of Rodriguez-Fornells et al. (2002) in which the activation in the left inferior prefrontal gyrus (BA 46/45) was related to inhibition of the on-target language. Brave (2003), during a cognitive switching task, found activity in the same regions but in the right hemisphere, including ventral anterior cingulate cortex and two regions of PFC (BA 9/10 and 46/10), and they related this activity to a need of sustain attentional control.

An Event-Related fMRI study (Abutalebi et al., 2007) investigating language control in early highly proficient bilinguals showed that naming in bilingual context increased activation in a large cognitive control network including the left ACC, the caudate nucleus, and the PFC and that this activation is greater if bilinguals are naming in a less exposed language. Moreover, activation of the PFC was also found during the single-language task, suggesting that this region is a potential candidate for the selection of different response alternatives (D'Esposito et al., 1995) and the switching between tasks (Rodriguez-Fornells et al., 2005). In contrast, activation of ACC and the caudate nucleus is engaged rather when two languages have to remain activated.

Wang et al. (2007) examined forward and backward switching in Chinese-English bilinguals performing a picture naming task. Relative to non-switch condition, language switch condition showed greater activation in the right superior prefrontal cortex (BA 9/10/32), left middle and superior frontal cortex (BA 8/9/46), and right middle cingulate cortex and caudate nucleus. Considering the direction of the switch, different activations were found. Forward switching (from L2 to L1) relative to L2 non switching, activated several frontal areas, left middle temporal gyrus, left angular gyrus, and the ACC. Strikingly, backward switching relative to L1 non-switching activated no regions involved in controlled language processing. Another study (Garbin et al., 2011) investigated the direction of language switching in early, proficient Spanish-Catalan bilinguals. The authors found that language switching compared to the non-switching condition elicited greater activation in the

head of the left caudate and the pre-SMA/ACC. Considering the direction of the switch, forward switching elicited activity in the left caudate, in contrast backward switching was associated with pre-SMA/ACC activity. Unexpectedly, when comparing backward versus forward switching activation in both left pre-SMA and right caudate was found. However, comparing forward versus backward switching none of these areas where activated. Finally, (Abutalebi, Della Rosa, Ding, et al., 2013) examined language switching in multilinguals: native German speakers who learnt Italian early in childhood and English later in life. They were high-proficient in their L1 and L2 and low-proficient in their L3. Switching between languages elicited greater activity in the pre-SMA/ACC regardless of language proficiency. In contrast, activity in left caudate nucleus was found in switching from the most to the least proficient language. The authors proposed that the pre-SMA/ACC has role in task monitoring and left caudate has a role in language selection depending on language proficiency.

Recent neuroimaging results have suggested a certain degree of neural overlap between language control and general cognitive control in bilinguals. In De Bruin et al. (2014), 23 trilinguals (L1-Dutch, L2-English, and L3-German) performed a picture naming task during an fMRI scan. They were highly proficient in their L1, good proficient in their L2 and intermediate in their L3. Behavioral results revealed that L1 was named faster than L2 and L3 in the blocked context but not in the mixed context. In the mixed context, switch trials were slower than non-switch trials. The pre-SMA and the rIFG, defined as regions of interest, showed higher activity for switches to the later acquired languages (L2 and L3) compared to non-switch trials. But switches to the L1 did not show increased activation compared to L1 non-switch trials. Moreover, switches to L2/L3 compared to switches to L1 showed more activation in the rIFG and the pre-SMA. These results have been interpreted as the involvement of domain-general inhibition areas in language switching and as a greater need of inhibition when switching to the non-native languages.

To our knowledge, only two studies had compared directly neural activity in language switching task with neural activity in non-linguistic switching task within the same participants. de Baene et al. (2015) examined the overlap in brain activation of language control and domain-general control in early highly proficient bilinguals. The authors used a three language switching paradigm (L1-Spanish, L2-Basque, and L3-English) and three task switching paradigms (motion, color and gender). The conjunction analyses showed that early highly proficient bilinguals relied on common areas for linguistic and non-linguistic control tasks, including the frontoparietal network (lateral and medial PFC, superior and inferior

parietal lobule). They also found that the precentral and the postcentral gyri were activated only for language control, but this discrepancy has been interpreted as a consequence of the difference between linguistic and non-linguistics tasks. Indeed, these regions are known to be related to articulatory processing and retrieval of phonological representations, two processes that are not involved in the non-linguistic switching task.

In Weissberger (2015) a group of Spanish-English highly proficient bilinguals underwent an fMRI experiment employing a hybrid (event-related and blocked) design. Participants performed a digit naming switching task and a color-shape switching task. In the shape-color task, participants were told to respond verbally instead of using button presses, in order to minimizing differences between linguistic and non-linguistic task. The authors observed the activation of the same network for both tasks. But the direct comparison of both task showed greater activation during language task in the blocked condition and switch trials in the mixed condition. In contrast, the direct comparison on stay trials in the mixed condition showed the opposite pattern, namely greater brain response for color-shape, suggesting that language task was less demanding on stay trials. The authors indicated that bilinguals might be "staying experts": even if bilinguals have practice switching, they have even more practice staying during monolingual conversation.

To summarize, studies using a blocked design show the importance of the PFC during language switching (Hernandez, 2009; Hernandez et al., 2001; Massa et al., 2016 for a review; Wang et al., 2009), confirming the role of this region (in both hemispheres) in language control. In contrast, event-related designs results show some discrepancies. Considering the direction of the switch, Abutalebi et al. (2007) and Wang et al. (2007) found opposite results: the former showed a need for a more controlled processing during backward switching, while the latter found activation of the neural language control network only during forward switching. Moreover, the role of the PFC and the ACC are still discussed (Struys, 2013): Hernandez et al. (2001) suggested that the PFC subserved language inhibition and selection, in contrast (Abutalebi et al., 2008) suggested that this role is subtended by the ACC. Regarding the question about the neural overlap between language control and general cognitive control in bilinguals, more studies need to be realized to shed light on this topic.

6 Neurostructural plasticity and language control

In the domain of brain plasticity, two studies (Abutalebi et al., 2012; Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013) investigated brain structure changes in regions associated with language control. The first study (Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013) focused on GM density in the left putamen of a multilingual group. The authors found increased GM density in the left putamen in multilinguals compared to monolinguals and they observed that this region was activated during picture naming in the least proficient language (that was also a late acquired language). This result could reveal that the greater articulatory load of the less-proficient language in multilingual speakers leads to structural changes in regions underlying this skill. The second (Abutalebi et al., 2012) investigated the role of ACC in cognitive control in early bilinguals. The authors found less activity in ACC in bilinguals compared to monolinguals during a Flanker task, suggesting that early bilingualism favor conflicting situation resolution. Moreover, they observed a positive correlation between the volume of the ACC and brain activity in this region, as well as behavioral measure. To summarize, these results are in line with the general-purpose that ACC is a region involved in conflict monitoring and that early bilingualism and use of two languages over life produce modifications on neocortical development.

CHAPTER 3: WHAT TYPE OF BILINGUALISM CREATES ADVANTAGES IN COGNITIVE CONTROL?

In Chapter 1 we have seen that bilinguals are not "*two monolinguals in one person*" (Grosjean, 1989) and that they use their languages for different reasons, in different manner and situations. Because of this heterogeneity, it is quite rare that bilingual subjects are equally fluent in their languages. In the psycholinguistic literature, two kinds of bilingual people are normally identified: early bilinguals and late bilinguals. This separation is made according to the age at which bilinguals have learned the second language. Even though a critical period is not well-defined for language acquisition, the period around 6 is considered optimal for a native-like second language acquisition (Flege, Yeni-Komshian, & Liu, 1999; Johnson & Newport, 1991; Lenneberg, 1967). However, these kinds of statements are an oversimplification, since they do not consider the different aspects of language learning. Language requires various types of knowledge and processing, which are supported by different brain structures, with different maturational timings. For instance, phonology, syntax and morphology may have different critical periods. Hence, the issue of critical periods in language learning needs to be considered in the context of the different linguistic domains (Costa & Sebastián-Gallés, 2014).

AoA, type of learning (explicit vs implicit) and language proficiency are factors that determine language representation in the brain (Fabbro, 2001). Functional imaging studies suggest a left hemispheric dominance for early, highly proficient bilinguals (Pratt, Abbasi, Bleich, Mittelman, & Starr, 2013). Interestingly, two studies comparing early and late multilinguals found that early bilinguals acquiring a third language (L3) activate more neural substrate than late proficient bilinguals acquiring an L3 indicating that language control might be influenced by early bilingualism (Wattendorf et al., 2001, 2012). However, in recent years, proficiency seems to gain a more important role in representation of languages in the brain (Abutalebi, Della Rosa, Ding, et al., 2013).

In Chapter 2, we have seen that a certain degree of neural overlap could subsist between language control and general cognitive control in bilinguals. Early studies in aphasia provided evidence that the mechanism of language switching could be located in the supramarginal gyrus, which is in the parietal cortex (Herschmann & Pötzl, 1983; Kauders, 1983; Pötzl, 1983). But, others found that a lesion to this area did not lead necessarily to impairment in language switching (Gloning & Gloning, 1983; Minkowski, 1983; Stengel & Zelmanowicz, 1933). This chapter reports recent studies that focused their attention on the investigation of the relation between language control and domain-general control and on the

question whether the variation in age of acquisition is related to an advantage in language control.

1 Bilingual benefits in cognitive control

1.1 Bilingual advantage over monolinguals

Evidence has shown that cognitive experience across the lifespan has significant effect on behavioral, neuropsychological and structural aspects of cognitive performance (Bialystok, 2009). For example, it has been shown that video game playing modifies visual selective attention (C. S. Green & Bavelier, 2003) and, furthermore, that stimulating experience has protective effects against cognitive decline with aging (Stern, 2003). As a result, researchers have started questioning whether bilingualism can have consequences on some aspects of cognitive performance. The core aspect of bilingual experience consists in the fact that both languages are always active and available and that there is no means to completely switch-off when only one of them is being used. Hence, since this language conflict entails a constant need of attentional control in bilinguals (Bialystok, 2009), it is reasonable to suppose a powerful effect on bilingual cognitive performance. One of the earliest studies suggesting that bilingual flexibility might spread to a more general cognitive advantage (Bialystok, 1999) was conducted comparing the performance of monolingual and bilingual children in a card sorting task. In this task, children are asked to sort a set of bivalent stimuli first by color and immediately after by shape. Hence, children have to remember the new rule in the second round and at the same time being able to ignore the information no more relevant in favor to the information that is now relevant. The authors found that bilingual children were better than monolinguals in the solving of experimental problems requiring high levels of control.

Commonly, the bilingual advantage has been tested through the use of tasks that involve ignoring distracting and conflicting information. One possible approach is the use of the traditional color Simon task (Figure 7). In this task, participants are told to associate a certain stimulus color with a spatial response and stimuli can be presented on the right or on the left side of the screen. For example, if a blue circle is presented, the participant has to push the left button, and in the case of a green circle, the right button has to be pushed whatever the position of the circle. The Simon effect predicts slower responses times when there is a

mismatch between the color of the stimulus and its location (in this example, the green circle placed on the left side of the screen). A small Simon effect is interpreted as indicative of a better ability in inhibition.

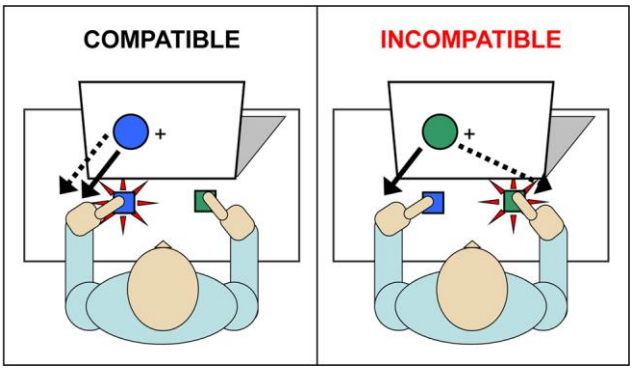

Figure 7. Example of a two color Simon task.

In a typical Simon task, subjects are shown a stimulus (i.e. a circle) on either the left or the right side of the display. Subjects are told to press either a left key or a right key based on the identity of the stimulus (e.g. the color of the circle). The location of the stimulus is irrelevant to the task, but it can be either consistent with the location of the response (e.g. a stimulus requiring a left key press appearing on the left side of the screen) or inconsistent with it (e.g. a stimulus requiring a right key press appearing on the left side of the screen).

In studies with bilinguals, researchers have been using a variant of this task: the arrow Simon task (Bialystok, 2006). In this variant, the stimulus is an arrow and participants are instructed to associate the direction of the arrow to a spatial response.

A third approach is the use of the Flanker task (Eriksen & Eriksen, 1974). In this task, a central arrow surrounded by four arrows (or flankers) that point in the same or the opposite direction is presented to the participant. Participants are instructed to ignore the direction of flankers and to concentrate only on the central arrow. This task is used to measure selective attention.

Hilchey and Klein (2011) put forward two assumptions on the cognitive control advantage in non-linguistic tasks derived from the training effect of bilingualism. The first one is called the bilingual inhibitory control advantage (BICA), and it has been specified 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).*

This hypothesis predicts superior performance for bilinguals on incongruent trials of interference tasks.

The first study (Bialystok, Craik, Klein, & Viswanathan, 2004) showing a bilingual effect on inhibition in the Simon task was conducted on two groups of middle-aged and older adults. Each age group was composed of 10 monolinguals speakers of English and 10 Tamil-English bilinguals. Results showed a smaller Simon effect in speed and accuracy for both bilingual groups and this advantage was greater for older participants. Similarly, a study from (Salvatierra & Rosselli, 2011) reported an advantage for bilinguals and it was conducted in English-Spanish bilingual younger and older adults and English monolingual controls. This study revealed that older bilinguals were more efficient at inhibiting irrelevant information than older monolinguals but such advantage was not seen in the younger sample. These two studies confirm the BICA hypothesis which affirms that bilinguals should show an inhibitory control advantage on the incongruent trials.

The second hypothesis posits that there is a global bilingual advantage on executive functioning not limited to inhibitory processes and it is referred to as the bilingual executive processing advantage (BEPA). According to this hypothesis, a bilingual advantage is present in both incongruent and congruent trials of interference tasks. But as argued by Costa and colleagues (2009) congruent trials do not entail conflict resolution processing since no conflict resolution is required. Hence, the overall bilingual advantage can be better expressed as 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). And in the case of bilinguals, the monitoring process is especially engaged when they are facing a mixed-language activity.

A study accounting for the BEPA hypothesis was realized by Bialystok, Martin, & Viswanathan (2005) in 4 different age groups (children, young adults, middle aged adults and older adults) of bilinguals and respective monolingual controls. The authors observed that children, middle aged adults and older adults performed more quickly and efficiently than monolingual controls in both congruent and incongruent trials but this pattern was not present in young adults. This discrepancy was explained with the hypothesis that the advantage of

bilingualism is not present when individuals are at the top of their attentional abilities. Young bilinguals performing a Simon task (Bialystok, 2006) and a Flanker task (Costa et al., 2009) while the number of response switches were manipulated showed the bilingual advantage was revealed in the condition that required most controlled attention and monitoring to resolve the conflict. The bilingual advantage in congruent and incongruent trials was also found in the attentional network task (ANT; Costa, Hernandez, & Sebastián-Gallés, 2008), that is a combination of a cue reaction time task (Posner, 1980) and a Flanker task (Eriksen & Eriksen, 1974).

Furthermore, bilinguals who tend to switch frequently on a daily basis showed better performance in a non-linguistic switch task (Prior & Gollan, 2011; Soveri, Rodriguez-Fornells, & Laine, 2011), confirming a possible transfer of language switching abilities into domain-general switching. Three sociolinguistic factors are expected to modulate bilingual effects on monitoring (Costa et al., 2009). The first is the functional distribution of languages in society. If bilinguals live in diglossic sociolinguistic environments where the two languages are used in separated contexts, they may not show advantages in monitoring processes since they are rarely confronted with switching situations. The second factor is the degree of bilingualism in the society. In societies where bilingualism is widely spread, the chances of having bilingual conversation are higher, hence the need for language monitoring too. The third factor is the degree of similarity between two languages that maximizes the chance for bilingual conversations. In sum, according to Costa et al. (2009), the higher the possibility to engage a bilingual conversation the higher the need of language control and hence higher the effect of bilingualism in monitoring processes involved in executive functioning in general.

Some neuroimaging studies have investigated the issue of bilingual benefits in executive control too. Garbin et al. (2010) compared a group of 19 Spanish-Catalan early bilinguals with a group of 21 Spanish in a color-shape switching task during an fMRI scan. At the behavioral level the bilingual advantage was observed as in previous studies and, interestingly, at the neural level they found that bilingual experience may change the lateralization and localization of cognitive processes involved in task switching. Compared to bilinguals, monolinguals showed increased activation in the right IFG and bilinguals showed more activity in the left IFG. Results of this study exhibit that early bilingualism may lead to changes in the lateralization and localization of cognitive processes underlying cognitive control skills. Typically, general switch tasks using non-linguistic tasks showed right inferior

frontal cortex activity (Robbins, 2007), while bilinguals language switching showed activation in the left inferior frontal gyrus (Abutalebi & Green, 2007). Interestingly, in this study activity in this region was related to behavioral facilitation in bilinguals and moreover, bilinguals did not recruit the same regions that are traditionally associated with task switching in monolinguals, as the inferior parietal lobule and the ACC. On the contrary, in another study (Abutalebi et al., 2012) the ACC was the only common region elicited in the Flanker task in bilinguals and monolinguals, but the activity in this regions was reduced in bilinguals, suggesting a bilingualism benefit for resolving cognitive conflicts.

1.2 Early bilingualism advantages

Studies that compare bilingual groups to monolingual controls have found evidence for a bilingual advantage in non-linguistic cognitive control abilities due to the daily control of two languages. But, considering the high variability within the bilingual population, it is worth investigating some factors regarding the differences within the bilingual population. In this section, we will discuss the effect of AoA on the presence of a cognitive control advantage. Based on the evidence of better executive functioning in bilinguals compared to monolinguals, it is plausible to suppose an advantage in bilinguals who have been exposed more extensively to multiple languages. In line with the literature on early language acquisition, the *early bilingualism effect hypothesis* postulates that a higher bilingual advantage should be evidenced in bilinguals who have started using more than one language on a daily basis early in life (Hilchey and Klein, 2011). Recently there are more and more studies that try to demonstrate how early practice leads to general cognitive benefits and this is not the case only for bilingualism; for instance, it has been found in children that music enrichment programs lead to important cognitive benefits (Črnčec, Wilson, & Prior, 2006).

To our knowledge few studies have compared two different populations of bilinguals in general cognitive control tasks. Some studies have investigated the early bilingualism effect in simultaneous and successive bilingual children (Carlson & Meltzoff, 2008; Poarch and van Hell, 2012), others have compared early and late bilingual adults (Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). For instance, one of the first study examining the bilingual effect reported performance of two bilingual groups of six year old children and a monolingual group in an ANT task (Carlson & Meltzoff, 2008). One bilingual group consisted in simultaneous bilingual children who have been exposed from birth to Spanish

and English. The second bilingual group consisted in children attending a language immersion school in which they received instruction in English for half of the day and in either Spanish or Japanese for the other half. The authors found better performance in simultaneous bilinguals in the ANT task and other executive function measures when added the age, verbal ability, and parent education levels as covariate of the statistical model.

The study of Poarch & van Hell (2012) found an early bilingualism advantage for early trilinguals and bilinguals (Figure 8). They compared four age-matched groups of children (5 – 8 years old): German second-language learners of English, German-English early balanced bilinguals, early balanced trilinguals, and German monolinguals. All groups performed a Simon task and the bilingual and trilingual groups an ANT test.

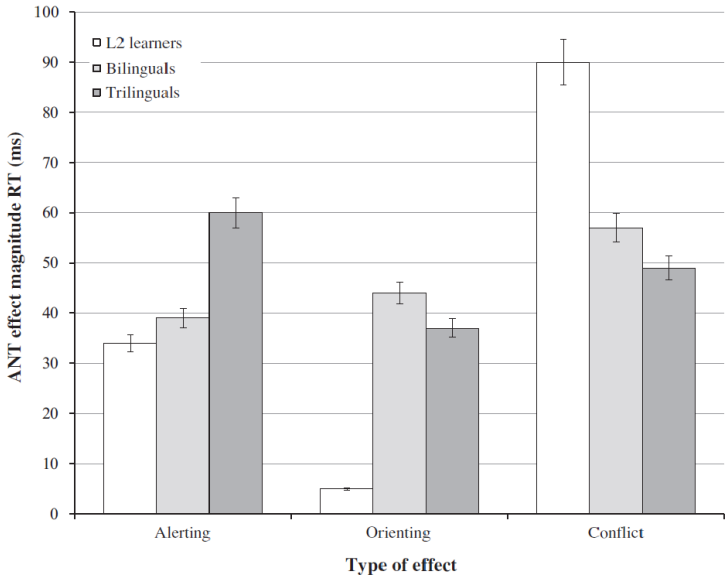

Figure 8. Effect magnitudes in the ANT across three bilingual populations (Poarch & van Hell, 2012, p. 546).

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.

The early bilinguals and trilinguals displayed an early bilingualism effect over the monolinguals and marginally over second-language learners in the Simon task, indicating that the language control continuously exercised by the bilinguals and trilinguals has a more general effect on attentional control mechanisms. In the ANT, bilinguals and trilinguals displayed enhanced conflict resolution over second-language learners. These results corroborated earlier findings revealing enhanced executive control abilities in early bilinguals. Moreover, dealing with a third language seems not to induce greater benefits than dealing with only two languages.

Regarding the comparison between bilingual adults, a study failed to find the early bilingualism effect examining the efficiency of executive attention in two groups of early and late Chinise-English bilingual adults and one group of English monolinguals performing a Flanker Task (Tao et al., 2011). The results replicated a bilingual advantage over the monolingual groups, but only a qualitatively difference were found between early and late bilinguals with respect to how each group differs compared to monolinguals. The authors concluded that early L2 acquisition is not essential for the enhancement of conflict resolution processes, although it may play a part in the emergence of efficient monitoring processes. On the contrary, Luk, De Sa & Bialystok (2011) showed that early bilinguals have better performance than late bilinguals and monolinguals in conflict resolution during a Flanker Task. Their results showed a relationship between more experience of active bilingualism and greater advantage in cognitive control, suggesting an active role of AoA. Surprisingly they could not replicate the bilingual advantage between late bilinguals and monolinguals.

2 The reconsideration of the bilingual advantage

Studies have failed to display a clear-cut evidence of the bilingual advantage. The replication of some of the effects indicating cognitive advantages in bilinguals is not always obtained and it seems to be limited to specific experimental conditions (Colzato et al., 2008; Costa et al., 2009). For instance, Paap & Greenberg (2013) failed to find the existence of BICA and BEPA in 3 studies in which bilinguals were compared to monolinguals on 15 indicators of executive functions; moreover, they found a disadvantage for the bilingual group in the Simon task. The authors concluded that the language control that bilinguals need for monitoring their communication, language switching, or suppressing the interference of the non-target language is encountered also in monolingual speech. Indeed, in daily communication monolinguals also have to monitor for signals regarding turn-taking, sarcasm, change of topic, or change in register, etc. And even if they do not have to face the problem of suppressing translation equivalents, they constantly have to decide among semantically and syntactically alternative candidates. The authors concluded 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" (Paap and Greenberg, 2013: 256).

In a recent article, Paap, Johnson, & Sawi (2015) affirmed that more than 80% of the studies for bilingual advantage conducted after 2011 observed null results and raised the issue of biased publication and questionable research practice. Moreover, the media has also had a role in consolidating the idea of a strong bilingual advantage and accepting it as common wisdom.

2.1 The "file drawer problem"

The "*file drawer problem*" was coined by Rosenthal (1979) to indicate the tendency of researchers to submit only experiments with significant results and set aside the one with null results. de Bruin, Treccani & Della Sala (2015) searched for conference abstracts and provided evidence that studies with positive results are favored over studies with null or negative effects. The authors point out two possible factors: 1) the authors decide not to publish studies with null or mixed results; 2) reviewers and editors are more prone to reject articles reporting null, negative, or mixed results than manuscripts reporting positive effects.

2.2 The confounding variables

Hilchey, Saint-Aubin & Klein (2015) advanced the need of a more systematic and rigorous effort to control factors that affect executive functions. They reported an excessive use of covariables susceptible to affecting EF instead of quantitative matched demographic variables and suggested that this practice may be the reason for the big number of studies reporting bilingual advantages. The issue of the socioeconomic status (SES) was pointed out by Morton & Harper (2007) showing that bilingual advantages tended to disappear when SES was controlled for. Bilingual and monolingual children with comparable ethnic and socioeconomic backgrounds showed similar performance in their study (Morton & Harper, 2007) that in terms of task, methods, and design was a direct replication of Bialystok et al., (2004).

Another point concerns the mixing or misunderstanding of two terms, mainly in research testing older adults: the immigrant status and bilingualism. It has been suggested that bilingualism might have a role in the onset of mild cognitive decline or dementia. But some of these studies confounded bilingualism with immigrant status (Bialystok, Craik, & Freedman, 2007) and when the immigrant status is controlled for, bilingual benefits were found in the immigrant group, but not in the nonimmigrant bilingual group (Chertkow et al., 2010). This suggest that the immigrant status, and not bilingualism, has an important role because it is associated with higher intelligence that, in turn, is associated with delays in dementia onset (Fuller-Thomson & Kuh, 2014).

2.3 The ANCOVA issue

Another issue is the use of the ANCOVA test in order to control statistically differences between groups. "*"Control" is altogether the wrong metaphor for understanding what ANCOVA accomplishes*" (G. A. Miller & Chapman, 2001: 42). A critical assumption of ANCOVA is that covariate and groups are independent, thus when there are systematic differences in the covariate across groups, results are uninterpretable (Paap et al., 2015). In studies looking for the bilingual advantage, this questionable use of ANCOVA is quite common (Blom, Küntay, Messer, Verhagen, & Leseman, 2014; Marzecová, Asanowicz, Krivá, & Wodniecka, 2013; Prior & Gollan, 2011; Tao et al., 2011). When the ANOVA fails to find the advantage, covariates as parent's educational level or SES are included as covariates, and then the expected difference between the two groups are found. But the use of the covariate is inappropriate when there is significant difference for this factor across the groups. Demographic variables need to be measured and quantitative matched.

Research to understand how the bilingual brain adapts and how such adaptive change shapes the language control network are still needed. Rigorous methods are demanded in order to achieve a better theoretical understanding of the bilingual brain and explicate how bilingual language use contributes to creates an enriched environment.

3 General research question

3.1 Language assessment

The bilingual population is characterized by a great heterogeneity. Factors as age of acquisition, proficiency, manner of acquisition are known to influence the architecture of the language system and the neural network involved in the processing of languages. However, most psycholinguistic studies have paid little attention to the variation between bilingual individuals. In some studies, bilingual groups were composed by individuals with widely varying language backgrounds (Carlson & Meltzoff, 2008) or with different age of L2 acquisition (Weissberger et al., 2015). Another issue is the widespread use of self-assessment test and the lack of objective measurements to test language proficiency (Misra, Guo, Bobb, & Kroll, 2012) even though it has already been stated that the correlations between self-assessment and formal tests for language proficiency are generally low (de Bot, 2008). In addition, some studies focused their attention only on the assessment of the L2 and not on the native one, forgetting that the mother tongue is not always the best well-known or the dominant language. Moreover, assessment is often performed on only one aspect of language processing, for instance on vocabulary, and a lot of different techniques have been used: for instance, translation tasks, or linguist's evaluation of spoken language (Klein, Milner, Zatorre, Zhao, & Nikelski, 1999) or verbal fluency tests. Such variation in participant characterization makes comparison between studies very complicated. In Europe, the development of the Common European Framework of Reference allows the creation of generalized proficiency scales that can help in the comparison of proficiency levels between experiments. Sociolinguistic information such as the manner of L2 acquisition and the acquisitional setting (language caretakers), type of education (bilingual education, immersion); the contact with the language (type of language use, intensity and relevance of contact); or the motivation to learn the language and attitudes towards L1 and L2, are often missing.

A lot of studies compare monolinguals to L2 speakers, but bilingual population "*will typically show more variation than monolinguals*" (De Bot, 2008: 120), and that makes it very hard to compare this kind of populations. Neuroimaging studies investigating the representation of early and late acquired languages compare L1 and late L2 (i.e. Abutalebi et

al., 2008; Verhoef et al., 2009; Wang et al., 2009, 2007) or early L1 and L2, and a late L3, (i.e., Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013; Videsott et al., 2010; Vingerhoets et al., 2003; Yetkin, Yetkin, Haughton, & Cox, 1996) in the same population. And in the few experiments studying the variability in bilingual populations, relevant factors involved in the processes investigated are not always isolated in a satisfying way. For instance, Luk et al. (2011) investigated the relation between AoA and cognitive control comparing early and late bilinguals. However, the differences they found between the two groups may also be linked to lower proficiency of the late bilinguals in their L2 as shown by the picture vocabulary task. Another problem is the lacking justification for choosing a particular age range as "early" or late when studying early/late bilinguals. In the literature, so-called *early bilinguals* vary a lot with respect to AoA: some studies use the age of 3 as the maximal age for early bilingualism (Wattendorf et al., 2012), others the age of 5 or 6 (Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013; Hernandez, 2009; Weissberger, Gollan, Bondi, Clark, & Wierenga, 2015). And, as already discussed, an early start does not mean that much in itself: language development history must be taken into account.

One of the aims of this study is to carefully control for proficiency in both languages by means of an extensive language test battery. A group of early simultaneous bilinguals and a group of late sequential bilinguals undergo a sociolinguistic questionnaire, a language assessment test, a picture naming task and a verbal fluency test (category and letter) in their L1 and L2 in order to determine a measurement of language proficiency as completely as possible.

3.2 Language representations in the bilingual brain

The emergentist theory (Hernandez & Li, 2007) points out that two languages learned in early childhood develop in parallel and create independent cortical processing maps. On the contrary, a language learned later in life will be less independent and more attached to the first language "*like a parasite feeding off its host, the first language*" (Hernandez, 2013: 155). In other words, unlike adult learners, early bilinguals create two language systems that are translated into separate cortical processing maps. Hence, "*early learning promotes future*

learning that conforms to and builds on the patterns already learned, but limits future learning of patterns that do not conform to those already learned" (Kuhl, 2004: 832).

AoA has consequences in non-linguistics domains as in birdsong and musical abilities. In the linguistic domain, articulation of speech sounds as a sensorymotor processing, the ability to control and coordinate the speech apparatus (tongue, lips, jaw, larynx, etc) showed an effect of early exposure (Hernandez & Li, 2007). It is not recent the idea that language is a sensorimotor ability in humans (Lieberman, 2000; Zatorre, 1989) and an association between AoA and sensorimotor processing has been shown (Hernandez & Li, 2007). Systems learned earlier (i.e. a language) rely more on speech sound and motor systems, whereas later learned systems depend more on complex processing tied to the prefrontal cortex. Hence, the processing of a L1 and a later learned L2 differ at the level of early sensorimotor processing and later higher cognitive processing respectively (Hernandez, 2013).

Evidence has been found that L1 and L2 seem to share the same brain language system (Frenck-Mestre, Anton, Roth, Vaid, & Viallet, 2005; Hasegawa, Carpenter, & Just, 2002; Illes et al., 1999; Kovelman, Baker, & Petitto, 2008; Mahendra, Plante, Magloire, Milman, & Trouard, 2003) as well as a third or subsequent languages (Briellmann et al., 2004; Vingerhoets et al., 2003). But some studies observed at least partly separate representations of languages in bilingual individuals. Micro differences in processing the L1 and the L2 were related to differences between languages with respect to proficiency and AoA. Studies on representation of language in L2 learners observed activation of multiple additional brain regions in processing the less proficient L2 (Chee, Hon, Lee, & Soon, 2001; Perani et al., 1998). However, even though some studies revealed a reorganization in terms of language representation with the increase of L2 proficiency, late bilinguals with comparable levels of proficiency showed a higher amount of activation in L2 than L1 (Kovelman et al., 2008; Perani et al., 2003; Vingerhoets et al., 2003; Wartenburger et al., 2003). As regards the age of acquisition, Kim et al. (1997) revealed spatially more separated activations in Broca's area in late bilinguals who had learned their L2 in late adolescence, whereas early bilinguals showed overlapping activation. Studies in which early and late bilinguals were directly compared revealed higher activation (Mahendra et al., 2003; Wattendorf et al., 2012) and low variability in brain activation (Bloch et al., 2009) in early bilinguals allowing researchers to assume an early neural signature of representation of languages.

L2 learning has many consequences (Bialystok, 2009), however the impact of the age of L2 acquisition is still not well established. The present study examines the neural substrates underlying overt language production by comparing two populations of bilinguals. We will investigate whether the neural activation in simultaneous early bilinguals, who have learned the two languages from birth, differs from the neural activation in late bilinguals, who have learned the L2 later in life. In the domain of monolingual vocabulary learning, words that have been learned earlier activate brain areas that are involved in speech and sound processing, whereas words learned later activate areas involved in the processing of meaning. Without reducing language acquisition in bilinguals to monolingual acquisition of words, we can expect some similarities between these two AoA effects. Indeed, due to brain maturation children and adults are equipped with very different neural and cognitive configurations that have a large impact on acquisition skills (Hernandez & Li, 2007). We investigated the cerebral network involved in picture naming in early bilinguals compared to late bilinguals to establish the influence of early simultaneous learning of two language systems compared with late, successive learning.

3.3 Language cognitive control in the bilingual brain

Typically, psychological studies use the switch tasks in order to investigating cognitive control. Switch tasks are composed by single task blocks and mixed task blocks. In the single task blocks, participants perform only one task. Within the mixed blocks, participants are cued to switch tasks (switch trials) or to perform the same task as in the preceding trials (stay trials). In the same line, one of the most popular tasks used to study the bilingual language control, is the language switching paradigm. Bilingual speakers have to switch from a language to another depending on the cue. Normally, they are asked to name picture or digits in both languages. Language switch tasks and domain-general cognitive control tasks show the same effects, the so-called “switch cost” (Calabria, Hernandez, Branzi, & Costa, 2012). This refers to longer response latencies and poorer accuracy during switch trials. In this context, it is interesting the existence of asymmetric switch costs, referring to the variation of the magnitude of the local switch cost depending on the relative difficulty of the two tasks. Local switch cost tends to be larger when switching from the more difficult to the easier task than the opposite. Hence, when performing a language switch task, switching from

a weaker L2 into a dominant L1 takes more time than switching from L1 to L2 (Meuter & Allport, 1999). This phenomenon is generally explained by the amount of inhibition required to inhibit a more dominant language (i.e., L1) during less dominant language trials (i.e., L2). Critically, several studies investigating this asymmetry reported symmetric switch costs in early highly proficient and balanced bilinguals (Costa & Santesteban, 2004) also when they are using their low-proficient L3, suggesting the existence of a specific-language switching mechanism and a shift of this mechanisms to processing of the less proficient L3.

Neuroimaging studies observed that the neural correlates of language switching includes the DLPFC (Hernandez, 2009; Hernandez et al., 2001; Wang et al., 2009, 2007), the ACC (Abutalebi et al., 2007, 2008; Garbin et al., 2011), and the caudate nucleus (Abutalebi et al., 2007; Crinion et al., 2006; Garbin et al., 2011), the superior and inferior parietal lobe (Khateb et al., 2007; Price et al., 1999; Rodriguez-Fornells et al., 2002), the SMA (Abutalebi et al., 2008; Wang et al., 2007), the inferior frontal gyrus (Abutalebi et al., 2007, 2008; Hernandez et al., 2001; Price et al., 1999), the precentral gyrus (Khateb et al., 2007; Wang et al., 2009). This network is similar to a domain-general neural network of executive control (Abutalebi & Green, 2007) and it is activated when bilinguals speak a less proficient language or when the two languages have to remain available at the same time (Abutalebi, 2008).

As we have seen, language use and cognitive control are deeply tied up in bilingual language processing. In order to communicate successfully, bilinguals have to select the required language and avoid unwanted interference from the language not in use. Late highly-proficient bilinguals are able to produce and understand complex sentences in a language different from their own mother tongue; in early bilinguals this ability is developed since early childhood, and often practiced during adulthood. This situation leads to a life-long experience with language switching in individuals with a high proficiency in both languages, an activity that it is at the core of language control.

The sample of bilinguals explored in our study corresponds to speakers that use the two languages on everyday basis, and have a very good command of both of them but differ on the age of acquisition to the L2. We expect that lower activation in areas involved in response inhibition, response selection and monitoring, i.e., SMA, DLPFC and ACC, in bilinguals who have started using more than one language on a daily basis early in life given the necessity to manage two languages during the development of executive control mechanisms. The present study tries to evaluate the effect of early language acquisition in

terms of response latencies and neural correlates of language switching comparing two bilingual groups of early simultaneous bilinguals and late sequential bilinguals that are matched for proficiency. To date, we do not have direct evidence of the influence of early L2 learning on the brain areas involved in language control because a) few imaging studies directly compared early and late bilinguals and b) to our knowledge, no study compared directly these two populations on a picture naming switch task. Finally, since language switching has been shown recently to depend on general cognitive control abilities (Linck, Schwieter, & Sunderman, 2012), all participants of our study not only are matched for proficiency but they are also tested on their cognitive control abilities (flexibility, inhibition) through a selection of neuropsychological tests in order to control their cognitive abilities.

3.4 Brain plasticity

Learning leads to functionally and physically changes in the brain. The experience of learning a new language is often accompanied by anatomical changes in brain structure in terms of increase of grey matter density and cortical thickness, or enhancing of white matter integrity (Li, Legault, & Litcofsky, 2014). Studies investigating structural changes in the bilingual brain are quite recent in comparison with functional neuroimaging methods. They have shown that bilingualism induced structural changes in different neural regions, including left inferior parietal lobule (Mechelli et al., 2004) the ACC (Abutalebi et al., 2012) and the IFG (Klein et al., 2014). In other domains, studies revealed that structural changes are originated by functional demands. For instance, Maguire et al. (2000) found that taxi drivers in London have a higher volume of GM in the posterior hippocampus, a region that underlies navigation-related skills. It is clear that the experience of a second language learning leads to structural changes but it remains still to be understood "*when and how such changes may occur, what learner variables modulate these changes, and what environmental factors may enhance, attenuate, or else minimize such changes*" (Li et al., 2014: 311).

The comparison of two groups who differ in terms of the onset of L2 acquisition gives the opportunity to explore the possible influence of variation in early language experience on the brain structure modifications. These two groups vary by the lengths of exposure to a second language and the manner of acquisition. Early simultaneous bilinguals had been using

both languages for the entire life, while late bilinguals started the use of the L2 later. Our expectation is that learning two languages early in life might shape the brain structure in terms of higher thickness in bilingualism-related regions. Since the brain is affected differentially to variations in early sensory experience (Neville & Bavelier, 2002), it is likely to presume to find a signature in structural plasticity for early language experience. Here we used an automated and direct measurement of cortical thickness from MRI scans to detect anatomical differences among individuals who acquired two languages simultaneously early in life and individuals who learned two languages sequentially, acquiring the L2 late in childhood.

- Goal 1 – Language assessment: to carefully control for proficiency in both languages by means of an extensive language test battery.
- Goal 2 – Language representation in early and late bilinguals: to examine the neural substrates underlying overt language production and whether the neural activation in simultaneous early bilinguals differs from the neural activation in late bilinguals.
- Goal 3 – Language representation of cognitive control in early and late bilinguals: to investigate whether life-long exposure to language conflict has an effect on the neural network subserving language control.
- Goal 4 – Structural plasticity in the bilingual brain: to find a signature in structural plasticity for early language experience in bilingualism-related regions.

CHAPTER 4: METHODS AND MATERIALS

1 Magnetic resonance imaging (MRI)

MRI is an imaging technology that allows the creation of high quality images of the human body. MRI is based upon the principles of nuclear magnetic resonance (NMR). This technique is non-invasive and does not employ damaging radiation. It uses a very powerful magnet to excite and detect the change in the direction of the rotational axis of protons present in the water inside the tissues of the body. An MRI scanner forms a very strong magnetic field (measured in tesla) around the area to be imaged. The scanner produces a radio frequency current that creates a varying magnetic field. The protons absorb the energy from the variable field and flip their spins. When the field is turned off, the protons gradually return to their normal spin, a process called precession. The return process produces a radio signal that can be measured by a receiving coil and made into anatomical images.

Structural MRI scans allows us to measures gray matter and white matter of the brain. Gray matter consists principally of neural cell bodies whereas the white matter consists of axons and support cells (Li et al., 2014). Some measures that can be obtained from anatomical images are gray matter and white matter density and volume, cortical surface area, and cortical thickness (for complete a review see Marie & Golestani, 2017). Gray matter density or volume has been one of the most common measure of anatomical brain changes but its measures is not direct and relies on voxel-based-morphometry (VBM), a voxel-by-voxel analysis of the tissue concentration. Unlike gray matter density or volume, cortical thickness allows a direct measure of the thickness of gray matter providing sub-millimeter accuracy (Li et al., 2014).

In addition to structural imaging, MRI can also be used to visualize functional activity in the brain. Researchers measure increasing or decreasing changes in blood oxygenation (neurons use more oxygen when they are active), while a subject performs an experimental task. This measurement is called blood-oxygen-level dependent (BOLD) contrast.

The combination of anatomical and functional information supplied by magnetic resonance imaging provides a powerful means to investigate the brain’s structural and functional organization.

2 Population

2.1 Inclusion criteria and assessments

All participants took various pre-tests to assess if they met the inclusion criteria. The inclusion criteria for all participants were:

- ≥ C1 level of CEFR (Common European Framework of Reference for Languages) in both French and English.
- Acquisition of both languages before age 3 or of L2 after age 10
- Age > 18 years
- Right-handed (Oldfield > +80).
- At least 12 years of schooling (French BAC)

The parameters of exclusion were:

- MRI contraindication as: claustrophobia, pregnant or breastfeeding women, addiction, metal intraocular lens, heart pacemaker, metallic foreign body, important neuropsychiatric disorders, surgical clips, refusal of being informed about an anomaly detect during fMRI scan, background history of epilepsy, person under legal protection.
- MMSE score < 26
- Any medical or psychiatric issues
- Age of acquisition of one of the language between 3 and 10 years

2.2 Recruitment

We recruited participants posting announcements posted at the University of Toulouse, at the engineering schools (i.e., ENSEEIHT), on-line through the web page RISC (http://www.risc.cnrs.fr, *Relais d'information sur les sciences de la cognition*) and a Facebook page for English Speaking in Toulouse. All participants deliberately decided to participate at this study, and contacted the examiner without any pressure. As recommended by the ethical research committee (CPP13-025/2013-A01155-40), all participants provided a

formal written consent for participating to this study. All volunteers received 80€ for their participation.

Prior to the experiment, participants took a test battery including language tests, neuropsychological tests and a medical examination. Examination sessions were conducted as follows:

Day 1: Language proficiency assessment.

Day 2: Shipping of the information letter about the research by mail and signature of the formal written consent.

Day 3: Medical examination, neuropsychological assessment and fMRI session.

Day 4: A phone call ensuring participant health condition after the MRI session.

All subjects passed all tests. During day 1, participants took the language tests, including a language assessment test, verbal fluency task and picture naming task. The language assessment test was provided first in order to ensure that all participants had at least C1 level in both languages. The tests in English and in French were taken the same day. This was due to timing constraints, as some participants did not reside in Toulouse, we could not ask them to come twice for only 40 minutes. We performed the language tests in a counterbalanced order across subjects to avoid order effects. Half of the participants took all the tests at the beginning in their L1 and after in their L2 and vice versa. The order of the tests in each language was counterbalanced too. Half of participants began with the verbal fluency task followed by the picture-naming task and vice versa. The procedure is summarized in table 2. Before session 2, a conversation in the next language was provided in order to put the subject in the “language ambiance”.

After day 1, if the participant succeeded in the language assessment, a formal written consent was mailed to his personal address and an appointment for day 3 was arranged.

Table 2. Examples of language test order.

Early bilinguals	Session 1 Language	Test 1	Test 2
Subject 1	L1	Picture-naming task	Verbal fluency test
Subject 2	L1	Verbal fluency test	Picture-naming task
Subject 3	L2	Picture-naming task	Verbal fluency test
Etc…	L2	Verbal fluency test	Picture-naming task
Late bilinguals			
Subject 1	L1	Picture-naming task	Verbal fluency test
Subject 2	L1	Verbal fluency test	Picture-naming task
Subject 3	L2	Picture-naming task	Verbal fluency test
Etc…	L2	Verbal fluency test	Picture-naming task

This table shows the counterbalanced order in which participants took language tests.

During day 3 participants attended the neuropsychological assessment including MMSE (Mini-Mental State Examination; Folstein, Folstein, & McHugh, 1975), Wechsler Adult Intelligence Scale (WAIS), Digit span subtest (Wechsler, 2000), Trail Making Test (TMT ; Reitan, 1958), Stroop Test (Stroop, 1935) and the medical examination necessary to perform the fMRI task.

2.3 Description of the population

Twenty healthy highly proficient French-English bilinguals participated in the experiment. 12 were men and 8 were women between the age of 20 and 40 years old (early bilingual mean age=24.7, SD=3,3; late bilingual mean age=28.7, SD=6). Half of them were early bilingual speakers of French and English (Group 1). All of them started learning L1 and L2 in their early childhood (before the age of 3). Group 2 was formed by 10 late-bilinguals speaking French or English as L2. They started learning the L2 after 10 years (mean age=11; SD=1,2; Table 3). They could have either English or French as L1 or as L2. All subjects with a high level in a third language were excluded. All early bilinguals, except one, were born in a family with each parent speaking one of the two languages. Just one early bilingual has two French speaking parents but spent his infancy in the US and had an English caretaker. All

participants found very important to maintain a good L1 and L2 level. All subjects affirm to use both languages daily or at least weekly.

Table 3. Characteristics of participants of early and late bilinguals.

Subject	Age	Gender	L1	L2	AoA L2	Language level	
						L1	L2
Early bilinguals							
1	31	F	ENG	FR	< 3	C1	C1
2	22	M	FR	ENG	< 3	C1	C1
3	27	F	ENG	FR	< 3	C1	C1
4	22	M	FR	ENG	< 3	C1	C1
5	22	F	ENG	FR	< 3	C2	C2
6	20	M	ENG	FR	< 3	C1	C1
7	27	M	FR	ENG	< 3	C2	C2
8	26	M	FR	ENG	< 3	C2	C2
9	26	M	FR	ENG	< 3	C2	C2
10	24	M	FR	ENG	< 3	C1	C1
Late bilinguals							
1	25	M	FR	ENG	11	C1	C2
2	24	F	ENG	FR	11	C2	C2
3	29	M	FR	ENG	12	C2	C1
4	23	F	ENG	FR	10	C2	C1
5	24	F	ENG	FR	10	C2	C1
6	34	M	FR	ENG	10	C2	C1
7	23	M	ENG	FR	10	C1	C1
8	36	F	ENG	FR	11	C1	C1
9	40	M	FR	ENG	14	C2	C1
10	29	F	FR	ENG	11	C2	C1

The table illustrates age, gender, language learned, L2 age of acquisition, and language level for each individual subject. Language level was assessed by language assessment test (test ELAO). The description of the test is given in the next section.

3 Language assessment

Participants completed a series of language pre-tests assessing language proficiency and the use of their languages. These tests included a sociolinguistic questionnaire (Annexe

1). The aim of this questionnaire was to collect information on the linguistic profile of the participants, their education level, their lifelong professional activities and an overall actual exposure to a given language. A large section of the questionnaire was devoted to the assessment of their language skills (self-evaluation) in both languages, the age at which they started learning languages, the context of acquisition, and their current practice of languages in terms of time spent and context in which languages are practiced. For the self-evaluation of language skills, a six-level Likert scale was used in order to evaluate ability in reading, writing, comprehension and speaking. Many of the issues addressed in the questionnaire, such as the nature of extra-professional activities, years spent abroad or the context of languages use could not be evaluated in this work but can be analyzed later.

Level of proficiency was also assessed by the Efficient Language Assessment Online test (ELAO test, http://elao.accentlang.com/fr/index.html), a verbal fluency test (letter and category fluency), and a picture naming task. The ELAO test is a piece of language software available on the Internet and used at the University of Toulouse to assess their students before taking language classes. It is based on the automatic adaptation of level of questions. The skill areas targeted are: general active vocabulary, general passive vocabulary, the active grasp of grammatical structures, and listening comprehension. Each module contains 200 and 250 questions of which 15 to 30 are selected in random fashion to be presented to the person tested. At the end of the test the software displays the results screen for each module and a general mark based on the 6 levels of the European framework. All participants had to take this test in English and French and needed to obtain the proficient user level (C1 or C2) of the CEFR to be included in the experiment.

The verbal fluency task consisted of two conditions: category fluency and letter fluency. Participants are given 1 minute to produce as many words as possible within a semantic category (e.g., animals, tools, fruits etc.) or starting with a given letter. No repetitions, no words of the same family are allowed. This test allows the assessment of lexical access ability, the ability to retrieve the grammatical representations and sound forms of words from the mental lexicon (Levelt, Roelofs, & Meyer, 1999), also the executive control ability (Shao, Janse, Visser, & Meyer, 2014). EF components measured by this test are updating, cognitive flexibility, inhibition and effortful self-initiation (Shao et al., 2014). To perform the task, subjects must keep the instruction and the earlier responses in their working memory in order to avoid repetitions and irrelevant responses. Furthermore, participants often produce cluster of related words in succession and switch from a clusters to

another (e.g., pets, farm animals, aquatic animals) showing the ability to change the search criteria and switch from one category to the next. Participants were asked to perform these tests both in French and in English separately. They had to overtly produce as many French or English words as possible within 60 s. In English letter fluency task, the sequence of letters "F", "A" and "S" is usually employed. This sequence was selected on the basis of the frequency of English words beginning with these letters (Strauss, Sherman, & Spreen, 2006). Our participants were asked to generate words that start with the letter F, the English letter with higher frequency. In French, they were asked to produce words that start with the letter P, the French letter with higher frequency (Cardebat, Doyon, Puel, Goulet, & Joanette, 1990). In the category fluency task, participants were asked to produce words in the animal category.

The picture naming task consisted of three conditions: two blocked conditions (picture naming in English and picture naming in French) and a switch condition (alternate picture naming in French and English). For these tasks we selected fifty black and white line-drawings of objects taken from the Centre for Research in Language-International Picture Naming Project corpus CRL-IPNP (Szekely et al., 2005). We selected concrete nouns with high name and image agreement on the basis of data provided by Alario & Ferrand (1999). All cognates between English and French were discarded, as well as all compound nouns. Switches occurred in an unpredictable, counterbalanced fashion. Each picture was named once in French and once in English. Therefore, 50 images were showed in the blocked conditions and 100 in the switch condition, for a total of 200 trials. The target language was indicated by a color frame surrounding the picture: blue for French and yellow for English. Each trial was presented for 1500ms followed by a blank screen of 1000ms.

4 Neuropsychological assessment

Neuropsychological tests were conducted, including MMSE (Folstein et al., 1975), WAIS- Digit span subtest (Wechsler, 2000), TMT (Reitan, 1958) and Stroop Test (Stroop, 1935). These tests were performed in French for all participants.

The Digit span subtest of WAIS consists of two conditions. In the first condition, the digit span forward condition, participants must recall a series of numbers in serial order. In the second one, the digit span backwards, participants must recall a series of numbers

backwards. This subtest is typically used to measure working memory, mental manipulation, cognitive flexibility, rote memory and learning, attention, and encoding.

The TMT involves two conditions. Condition 1 is a sequential task using numbers. Participants have to connect numbers in ascending order from 1 to 25. Condition 2 is a double sequential task that requires participants to alternate between connecting numbers in sequence with letters in sequence from 1 to 13 and from A to L. The cognitive abilities tested are cognitive flexibility and inhibition of preservative responding.

The Stroop Color Word test consists of three conditions. In condition A participants read color names printed in black. In condition B participants name patches of color. In condition C a distractor is introduced: the names of colors across the page are printed in the ink of a different color. Participants have to say the name of the ink color while inhibiting the response induced by printed word. For example, the word blue would be printed in green ink; hence the expected answer is "green". 100 items are presented on the page. The time required to correctly read each section is used as the score. Errors are reported. This test evaluates response inhibition.

5 fMRI picture naming task

5.1 Stimuli

The picture naming task was presented to the participants during an fMRI scan. This task consisted of three conditions: two blocked conditions (naming in L1 or L2) and a switch condition (L1 and L2 context). E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) was used for the presentation of stimuli. A mirror attached to the top of the head coil allowed the participants to view stimuli delivered via a projector connected to a laptop outside the magnet room. To ensure that the correct answer was produced during the experiment, participants had to name the stimuli overtly. Responses were recorded with a microphone (FOMRI II) connected to a computer outside the scanner room. For the experiment we used a total of 168 different black and white drawings selected from the Centre for Research in Language-International Picture Naming Project corpus CRL-IPNP (Szekely et al., 2005). Each stimulus, 105 x 105 mm, was presented once for all three conditions, totaling 504

stimuli for each participant (Annex 2). Pictures were chosen such that names in French and English had no phonological similarity ("non-cognates"). Compound nouns were eliminated too. For instance, the picture of "ball", which is "balle" in French, and "butterfly", which is a compound name, were discarded. For information on frequency, name agreement and image agreement we referred to Alario & Ferrand (1999) for French, and Szekely et al. (2005) for English. Mean name agreement for the two languages was 91.1% for French and 92.1% for English. Mean picture familiarity for French was 3.1 and for English 3.4 out of 5 on a scale from 1 to 5. Half of the items were high-frequency words (English mean: 4.2; French mean: 70.6) and the other half were low-frequency words (English mean: 2.1; French mean: 26.7; see Table 4). In the two corpuses, frequency was calculated in two different ways, which explains the great difference in the values.

Table 4. Characteristics of items used in picture naming task.

Means	French		English	
	Low	High	Low	High
Word frequency	26.7	70.6	2.1	4.2
Picture familiarity	3.1		3.4	
Name agreement	91.1%		92.1%	

The value presented corresponds to the mean of each category. English word frequency taken from Szekely et al. (2005), French word frequency taken from Alario & Ferrand (1999). Picture familiarity is from a 5-point scale (1 a very unfamiliar object, 5 a very familiar object). Name agreement is given in percentage.

5.2 Experimental paradigm

The fMRI experimental design consisted of 6 runs, lasting 5 min and 75 sec each, where all conditions were presented in a pseudo-random way. In each activation block, 7 pictures were presented every 2950ms. The pictures were presented for 1500ms, followed by a fixation cross for 1000ms. Each trial started with a visual cue lasting for 450ms (an example of sequence is showed in Fig. 9).

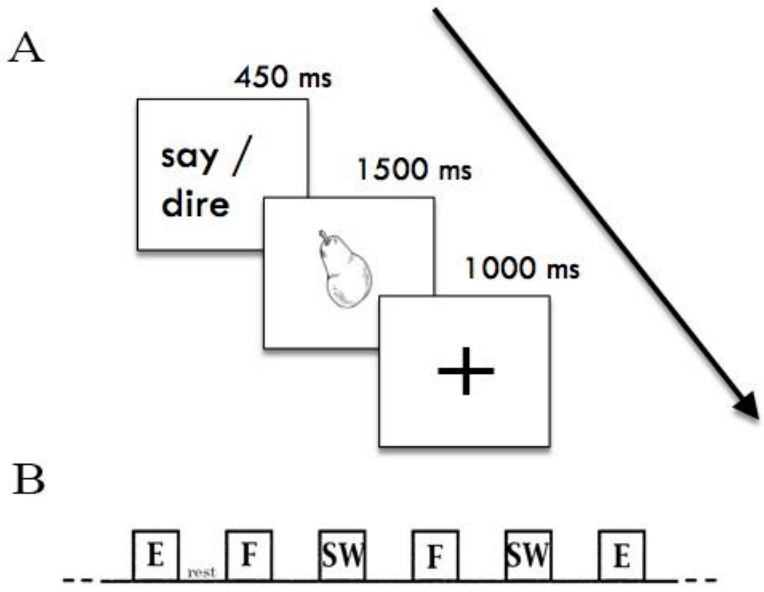

Figure 9. Experimental design.

A) This figure illustrates an example of a trial sequence: a visual cue was presented for 450ms, followed by a picture presented for 1500ms. A fixation cross lasting 1000ms was showed after each picture. B) Example of blocks within a session. This figure illustrates the alternation of the blocks. E= English blocked condition; F= French blocked condition; SW= switch condition

The cue, indicating the English word "say" or the French word "dire", instructed the participant of the language of response. In the mixed condition, the cue alternated on every picture from one language to the other. A similar paradigm was previously used by Hernandez et al. (2001) but in our study participants were instructed to name pictures overtly. The order of presentation of the 6 runs, composed of 12 activation blocks, was balanced across subjects. Each activation block was alternated with a rest period of 8850 ms (2950x3 ms), during which a fixation cross was presented and subjects were instructed to rest.

5.3 fMRI acquisition and imaging data analyses

5.3.1 Acquisition parameters

The experiment was conducted in one session lasting about 1 hour using a 3T- MRI Philips ACHIEVA (Philips Achieva, Best, the Netherlands) provided with an 8-channels SENSE head coil. This is a machine used only for research located on Neurocampus Baudot of Purpan Hospital (*Institut des Sciences du Cerveau de Toulouse*). Visual presentation was provided by a Toshiba video projector back-project on a transparent screen. Participants were equipped with a MR CONFON headphone and earplug as a protection from MRI noise.

A high resolution 3D anatomical image of the entire brain was taken before the fMRI task for each participant composed of 170 T1-weighted images (TR = 8,1ms ; TE = 3.7ms; flip angle = 8°; field of view (FOV) = 240x240 mm; voxel size = 1mm^3). Functional images were acquired using a T2 echo-planar imaging (EPI) sequence (TR = 2950ms; TE = 30ms; flip angle = 90°; field of view (FOV) = 240x240mm). Each volume was composed of 38 interleaved axial slices of 3 mm of thickness covering the whole brain (voxel size: 3 x 3 x 3 mm).

5.3.2 Images preprocessing

For each participant we obtained 117 functional images and a T1 anatomical image that were converted from DICOM format to NIFTI format using « MRIConvert » software (Smith, 2011).

5.3.2.1 Functional images analyses

The data were processed and analysed using Statistical Parametric Mapping (SPM12; (http://www.fil.ion.ucl.ac.uk/spm; Wellcome Department of Cognitive Neurology, London, UK), running on Matlab 8.6 (Math Works, Natick, MA). Slice-timing procedures were applied to all EPI images to correct for differences in acquisition time between slices. Functional images of each subject were realigned to the mean image to correct for

movements, co-registered to the structural image, normalized into the Montreal Neurological Institute (MNI) stereotactic space and smoothed by a 6-mm isotrophic Gaussian kernel. At first level, single subjects' data were analysed with a fixed effects model within the framework of the General Linear Model (Friston et al., 1994). The six motion parameters derived from the realignment step were included in the model as regressor of no interest in order to minimize the impact of possible head movements. The group averaged effects were computed with a random-effects model.

5.3.2.2 Analyses of imaging data

At the first level, single subjects' data were analysed with a fixed effects model within the framework of the General Linear Model (Friston et al., 1994). The six motion parameters derived from realignment stage were included in the model as regressor of no interest. The averaged group effects were computed with a random-effects model.

Three simple main effects were tested: naming in L1 (non-switch trials); naming in L2 (non-switch trials); and naming alternately in L1 and L2 (switch trials). Whole-brain t-tests contrasts, comparing statistical maps between three conditions, were conducted using a threshold of $p<0.05$ voxel-wise corrected for Family Wise Error (FWE) correction, with an extent threshold of 100 contiguous voxels. When no activation was found, we lowered the statistical threshold of $p<0.001$, uncorrected for multiple comparisons, with an extent threshold of 100 contiguous voxels. The anatomical location of significant clusters was determined using the xjView 8 toolbox for SPM (Cui, Li, & Song, 2011). Figures were created using MRIcron software (Rorden & Brett, 2000).

Regions of interest were defined following previous studies on language switching that have found dlPFC and ACC to be involved in language switching (Abutalebi et al., 2008; de Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014; D. W. Green, Crinion, & Price, 2006; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Wang, Xue, Chen, Xue, & Dong, 2007). Further analyses have been performed on three regions of interest (ROI): left ACC (x = -3, y = 14, z = 38), left SMA (x = -3, y = 2, z = 59) and left DLPFC (BA9/46, x = -45,y = 15,z = 25). ROIs of 10 mm spheres were generated with Marsbar ROI Toolbox (http://marsbar.sourceforge.net) to investigate the BOLD responses in these ROIs for the for switch vs. baseline contrast. Contrast values (effect sizes for the ROI) were obtained from the

single-subject contrast images and exported to SPSS for group level analyses. We used t-tests to identify effects of age of acquisition and established correlations with behavioral results.

5.3.3 Cortical thickness

We measured cortical thickness to detect anatomical differences among late and early bilinguals. An automatic measurement was performed on MRI 3D T1 images using Corthizon (Querbes, 2009). The Corthizon toolbox is a MATLAB toolbox which estimates the individual cortical thickness of each subject using the Laplace-based technique. Corthizon provided a measurement of cortical thickness across the entire brain excluding cerebellum at over 45 Brodmann areas (left and right hemisphere) and 90 gyri. Since every human being has a different brain, a normalization of cortical thickness was performed over all participants by dividing each participant's area score by the whole brain cortical thickness mean of each participant.

5.4 Audio processing

Participants' responses were recorded with a microphone (FOMRI II) connected to a computer outside the scanner room. A noise reduction of the acoustic characteristics of MRI was performed via OptiMRI software. This software helps to reduce and clarify noise in real-time during the fMRI process and creates pre-processing and post-processing wave files as we can see in figure 10.

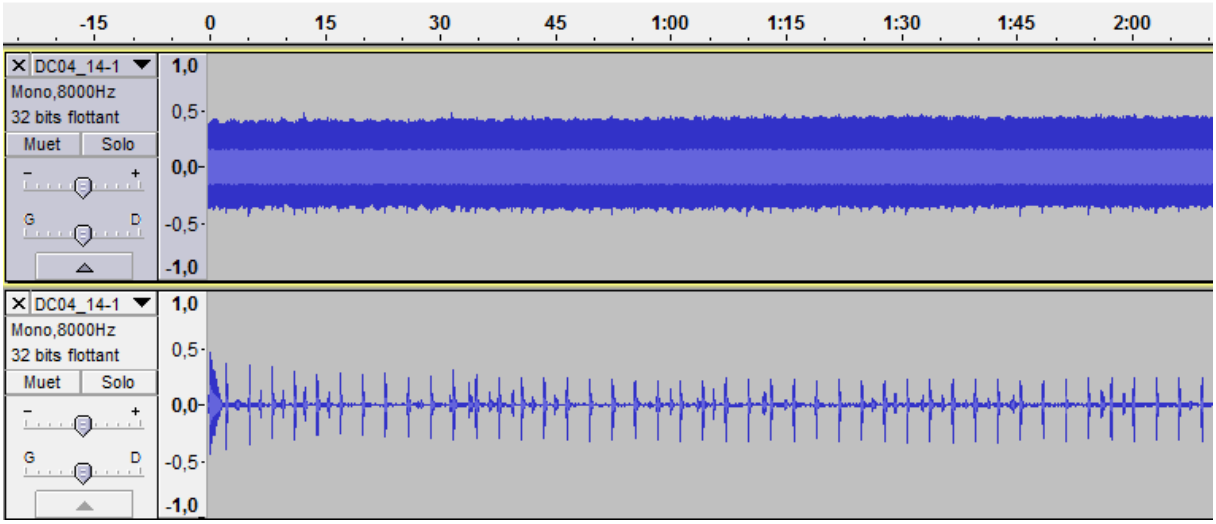

Figure 10. Audio file visualization.

The figure illustrates an example of pre-processing and post-processing audio files visualized via Audacity.

Semi-automatic analysis was performed to calculate response time (RT). Using a MATLAB-based speech segmentation program supplied by SAMoVA[1] team, IRIT, track markers for beginning of trial and beginning of speech production were automatically extracted and labelled as 'bruit" (French form for noise) and "parole" (speech) respectively (Figure 11). However, due to MRI noise which deteriorates the segmentation, track markers were then manually adjusted.

[1] https://www.irit.fr/recherches/SAMOVA/

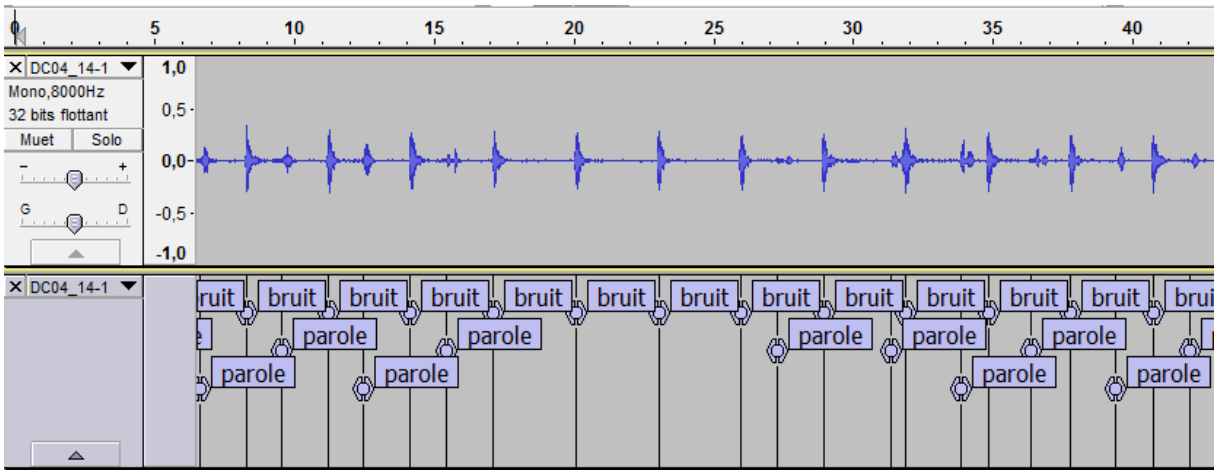

Figure 11. An example of track markers.

This figure illustrates track marker file and how the sound was labelled in Audacity. 'bruit" is the French form for noise and "parole" is the French form for speech.

Finally, using another MATLAB program, RTs in milliseconds are automatically extracted from the track marker file. The program subtracts the position time (given in msec) of the 'bruit' track marker from the position time of the immediately successive 'parole' track marker.

5.4.1 Audio recording judgement criteria

Two judges classified participant's responses basing their decisions on Snodgrass & Vanderwart (1980) criteria. Judgement criteria were as follows: a valid answer was the modal name given by Snodgrass & Vanderwart (1980) and Szekely et al. (2005) or a non-dominant name. Non-dominant names or names deviating from intended name, were accepted if they could correspond to the following classes: synonyms (a word having the same or nearly the same meaning, e.g., 'hen' for 'cockerel'), coordinates (as exemplars of the same category, e.g., 'bee' for 'fly'), component (part of, e.g., 'knee' for 'leg'), superordinate (e.g., 'insect' for 'ant') and subordinates (e.g., 'revolver' for 'gun'). The remaining answers, as well as cases of erroneous recognition of the stimulus corresponded to naming failures, or errors. Among naming failures, we recorded also non-responses before the trial end, code-switching (defined

as the use of the unexpected language), and babbling (defined as an incomprehensible and meaningless stream of sound).

CHAPTER 5: RESULT

1 Characteristics of the population

In this section, the results of the language and neuropsychological assessments are presented and compared between the two groups with a Student t-test model.

1.1 Language assessment

The self-evaluation test revealed a very high score for the two groups for both languages and no difference was observed between the two groups in L1 for global proficiency (early b.: 5.9±0.3, late b.: 5.9±0.3), speaking (early b.: 5.8±0.6, late b.: 5.8±0.6), comprehension (early b.: 5.9±0.3, late b.: 5.9±0.3; ts(18)=0, p=1]), writing [early b.: 5.5±0.9, late b.: 5.9±0.3;) and reading [early b.: 5.9±0.3, late b.: 5.9±0.3; t(18)=-1.232, p=0.232; see table 5]. These results indicate that both groups are equally highly proficient in L1.

Table 5. Mean scores in the self-evaluation test in L1.

L1 self-assessment	Early bilinguals	Late bilinguals	p
Global	**5.9 ±0.3**	**5.9±0.3**	**ns**
Speaking	**5.8±0.6**	**5.8±0.6**	**ns**
Comprehension	**5.9±0.3**	**5.9±0.3**	**ns**
Writing	**5.5±0.9**	**5.9±0.3**	**ns**
Reading	**5.9±0.3**	**5.9±0.3**	**ns**

Mean score and standard deviation for the L1 self-evaluation test evaluated on a 6-point scale from "poor proficiency" (response 1) to "excellent proficiency" (response 6).

Regarding the self-evaluation mean scores in L2, no difference was found for global proficiency [early b.: 5.5±0.8, late b.: 5.5±0.5; t(18)=0,p=1], speaking [early b.: 5.6±0.5, late b.: 5.6±0.5; t(18)=0,p=1], comprehension [early b.: 5.6±0.8, late b.: 5.7±0.4; t(18)=-0.325, p=0.749] and reading [early b.: 5.4±0.6, late b.: 5.7±0.4; t(18)=-1.116,p=0.279]. But we observe a lower level in writing skill for early bilinguals compared to late bilinguals [early b.:

4.6±0.8, late b.: 5.6±0.6; t(18)=-2.652, p=0.016, see table 6], indicating a lower confidence in the language in which they were not educated.

Table 6. Mean scores in the self-evaluation test in L2.

L2 self-evaluation	Early bilinguals	Late bilinguals	p
Global	**5.5±0.8**	**5.5±0.5**	**ns**
Speaking	**5.6±0.5**	**5.6±0.5**	**ns**
Comprehension	**5.6±0.8**	**5.7±0.4**	**ns**
Writing	**4.6±0.9**	**5.6±0.6**	**0.01**
Reading	**5.4±0.6**	**5.7±0.4**	**ns**

Mean scores and standard deviation for the L2 self-evaluation test evaluated on a 6-point scale from "poor proficiency" (response 1) to "excellent proficiency" (response 6).

We assessed both languages with language assessment software (ELAO) used at the University of Toulouse. All participants achieved a score of C1 or C2 of the European Framework of Reference for Languages (CEFR) that the software translates in a percentage score. No difference was found between the two groups for L1 [early b.: mean 88.9±5.8, late b.: mean 92.±2.9; t(18)=-1.546, p=0.1] and L2 [early b.: mean 87.0±5.2; late b. mean 84.7±4.9, t(18)=1.013, p=0.9], indicating that both groups have the same proficiency in both languages.

Participants took also two verbal fluency task (phonemic and semantic fluency) in French and in English. No difference was found between the two groups in L1 phonemic fluency [early b.: mean 14.4±5.1, late b.: mean 18.1±3.9; t(18)=-1.890, p=0.157], L1 semantic fluency [early b.: mean 22.2±4.3, late b.: mean 25.3±6.3; t(18)=-1.558, p=0.267], L2 phonemic fluency [early b.: mean 13.5±2.5, late b.: mean 14.6±2.0; , t(18)=-1.083, p=0.235] and L2 semantic fluency [early b.: mean 21.1±5.2, late b.: mean 22.3±5.6; t(18)=-0.806, p=0.394].

No difference between the two groups was observed in the preliminary picture naming task in L1 [early b.: mean 49.6±0.8, late b.: mean 49.3±1.6; t(18)=-0.354, p=0.728], in L2

[early b.: mean 48.4±1.2, late b. mean 48.3±1.5; t(18)=-0.161, p=0.258] and in the switch condition [early b.: mean 96.4±2.5, late b.: mean 97.8±1.6; t(18)=-1.416, p=0.322].

Table 7. Mean scores in language assessment tasks.

	Early bilinguals	Late bilinguals	p
Age[2]	24.7±3.3	28.7±6.0	ns
Gender	3(f) / 7(m)	5(f)/5(m)	-
AoA L2	0**	11±1.2**	0.001
L1 French/English	6 (F)/ 4(E)	5(F)/4(E)	ns
L2 French/English	4(E)/ 6(F)	4(F)/5(E)	ns
L1 proficiency	88.9±5.8	92±3.1	ns
L2 proficiency	87±5.2	85±4.7	ns
L1 Phonemic Fluency test	14.4±5.1	18.1±3.9	ns
L2 Phonemic Fluency test	13.5±2.5	14.6±2.0	ns
L1 Semantic Fluency test	22.2±4.3	25.3±6.3	ns
L2 Semantic Fluency test	21.1±5.2	22.3±5.6	ns
Picture naming task - L1	49.6±0.8	49.3±1.6	ns
Picture naming task – L2	48.4±1.2	48.3±1.5	ns
Picture naming task - switch	96.4±2.5	97.8±1.9	ns

Summary of characteristics of the two groups according to their age, gender (female (f), male(m)), AoA, mean scores in ELAO test, fluency task and picture naming task. Only AoA is significantly different (t<0).

To summarize, language assessment showed that the two groups are equally highly proficient in both languages and that they differ only for age of acquisition (Table 7). Only the self-evaluation test revealed a significant difference: early bilinguals show lower level of writing skills.

1.2 Neuropsychological assessment

General cognitive level was assessed via MMSE test (Folstein, Folstein, & McHugh, 1975 - French norms by GRECO; Kalafat, Hugonot-Diener, & Poitrenaud, 2003). All

[2] Age and AoA are expressed in years. Proficiency is noted on the basis of the two kinds of ELAO results: on a scale from 1 to 6 and in percentage.

participants achieved a score ≥ 28 (mean: early bilingual: 29.7±0.7, late bilingual 29.7±0.7). All participants were right-handed (mean: early bilingual: 92±9.2, late bilingual: 94±8.4) as confirmed by the Edinburgh Handedness Inventory (Oldfield, 1971).

During the neuropsychological assessment, participants performed three tests: WAIS test (digit span subtest), TMT and Stroop test.

An independent samples t-test showed no difference in span between early and late bilinguals for the forward subtest [early b.: mean 9.7±2.3, late b.: mean 9.2±1.9; t(18)=0.518, p=0.610], the backward test [early b.: mean 6.6±2.3, late b.: mean 7.2±2.6; t(18)=-0.553, p=0.587].

The results of the Stroop test showed that there was no difference between the two groups in the time it took to read the Word subtest [early b.: mean 45.2±7.7, late b.: mean 41.9±5.1; t(18)=1.129, p=0.274], the Color subtest [early b.: mean 51.9±6.6, late b.: mean 49.2±6.3; t(18)=0.936, p=0.362] and the Color-Word subtest [early b.: mean 70.2±12.1, late b.: mean 67±8.3; t(18)=0.689], as well as the interference score derived by subtracting the Color task score from the Color-Word score [early b.: mean 18.3±8.4, late b.: mean 17.8±6.9; t(18)=0.145, p=0.886].

No difference between the two groups was observed either in the total time required to complete each TMT subtest: the digit subtest [early b.: mean 25.2±4.0, late b.: mean 27.5±11.1; t(18)=-0.616, p=0.546] and the digit-letter subtest [early b.: mean 53.7±8.2, late b.: mean 48.3±14.1; t(18)=1.047, p=0.309]. No difference was also revealed by the difference score [early b.: mean 28.5±9.4, late b.: mean 20.8±14.5; t(18)=1.413, p=0.175] and the proportional score [early b.: mean 1.2±0.5, late b.: mean 0.9±0.8; t(18)=0.939, p=0.36].

Table 8 provides a detailed overview of the neuropsychological assessment scores and shows that the two groups have equal performance on all tests, indicating an equal level in working memory, cognitive flexibility and response inhibition.

Table 8. Mean scores of neuropsychological assessments.

Neuropsychological assessment	Early bilinguals	Late bilinguals	p
MMSE	29.7±0.7	29.7±0.7	ns
Oldfield	92±9.2	94±8.4	ns
WAIS test - Total	16.3±4.2	16.1±3.8	ns
WAIS test - Total Forward	9.7±2.3	9.2±1.9	ns
WAIS test - Total Backward	6.6±2.3	7.2±2.6	ns
TMT test - Digit score (A)	25.2±4.0	27.5±11.1	ns
TMT test - Digit-letter score (B)	53.7±8.2	48.3±14.1	ns
TMT test - Difference score (B-A)	28.5±9.4	20.8±14.5	ns
TMT test - Proportional score (B-A/A)	1.2±0.5	0.9±0.8	ns
Stroop Test - Word (A)	45.2±7.7	41.9±5.1	ns
Stroop Test - Color (B)	51.9±6.6	49.2±6.3	ns
Stroop Test - Color-Word (C)	70.2±12.1	67±8.3	ns
Stroop Test - Difference (C-B)	18.3±8.4	17.8±6.9	ns

The tables display the performance of both groups for the WAIS test (digit span: forward and backward scores), the TMT test [Digit (A), digit-letter (B), difference and proportional scores in seconds] and the Stroop test [Word (A), Color (B), Color-Word (C) and difference (C-B) scores in seconds].

2 Behavioral results

As we recorded the picture naming task during the fMRI session with a microphone, we could control the performance of the participants during the task. An analysis of the behavioral data, including accuracy and responses latencies (RT), was performed to clarify the interpretation of imaging results. Nevertheless, a late bilingual participant's performance was discarded because of a problem with the recording software. Analyses were performed on percentage of errors and corrected naming latencies after discarding outliers (3 SD above or below each participant; mean 2.5% of the total data). Statistical analyses were run in IBM SPSS Statistics for Windows, Version 19.0 Armonk.

2.1 Accuracy

Participants' production was analyzed to identify different errors. A total of 8.4% of trials were considered errors. Participants made 6.3% substitutions (erroneous recognition of the stimulus) and omissions, 1.7% code-switching, and 0.4% disfluent responses (as babbling). Early bilinguals made 9.6% of errors and late bilinguals 6.9%.

An ANOVA was performed also over type of errors with "type of error" ("omission", "code-switching" and "babbling") as within-subject factors and "AoA" ("early" *vs.* "late bilinguals") as between-subjects factor. A main effect of type of errors is found [F(2,34)=81.068, p=.000]. Post hoc tests were performed with Bonferroni correction for multiple comparisons, significant difference was found for all three types of trials. Most frequently, error type is omission of response. This is not surprising as participants were instructed not to answer if they were unsure or if they did not know the image to ensure that they are not stuck on the image since the task was quite fast-paced. A trend of AoA effect is found [F(1,17)=4.070, ns].

We conducted a repeated-measure ANOVA with "condition" (blocked and switch) and "language" (L1 and L2) as within-subject factors and "AoA" (early vs. late bilinguals) as between-subjects factor. An effect of language was found. Overall participants made more errors in L2 trials (10.7%) than L1 trials [7%, F(1,17)=8.937, p=.008]. A condition effect was also found, participants made more errors in switch trials (10.4%) than blocked trials [7.3%; F(1,17)=13.353, p=.002]. No difference between the two groups was found [F(1,17)=3.828, .ns].

2.2 Responses latencies

For response times (RT) on corrected trials, we analyzed 4376 trials for early bilinguals and 3881 trials for late bilinguals. Table 9 shows RT means of both groups in the blocked condition in L1 (early b.: 988ms, late b.: 994), L2 (early b.: 1000ms, late b.: 996ms) and in the switch condition in L1 (early b.: 1039ms, late b.: 1041ms), L2 (early b.: 1021ms, late b.: 1042ms). We conducted a repeated-measures ANOVA with "condition" (blocked and switch) and "language" (L1 and L2) as within-subject factors and "AoA" (early vs. late bilinguals) as between-subjects factor. Only one condition effect was found. Switch trial

responses (1036ms) were slower than blocked trial responses (995ms; F(1,17)=34.804, p=000. No AoA effect was found [F(1,17)=0.062, *.ns*].

Table 9. Responses times means in the picture naming task.

RTs	Early bilinguals		Late Bilinguals		Tot	
	L1	L2	L1	L2	L1	L2
Blocked	988 (05)	1000 (04)	994 (09)	996 (05)	991 (08)	998 (04)
Switch	1039 (06)	1021 (05)	1041 (08)	1042 (06)	1040 (07)	1031 (05)

This table illustrates the RT means of each group in the 3 conditions: L1 naming, L2 naming and switch naming condition. RTs are indicated in milliseconds with the standard error in brackets.

The results of the reaction time (RT) analysis of the picture naming task for each participant and condition are depicted in figure 12. We observe that the switch condition is effortful than the L1 and L2 blocked condition in all participants, except three (two early bilinguals, one late bilingual).

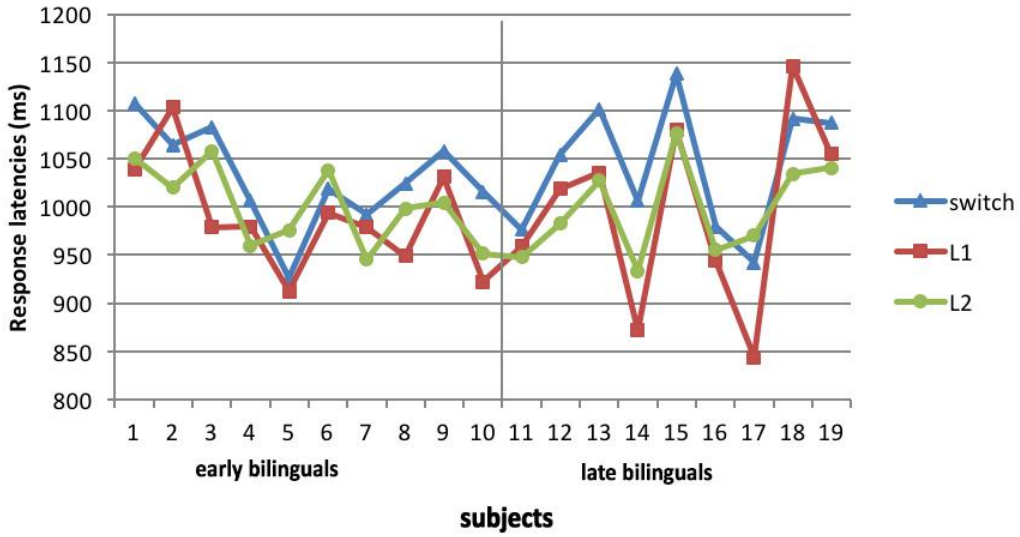

Figure 12. Participants' performance during the picture naming task.

The figure illustrates responses times of all subjects (=19) for all three conditions (L1 in red, L2 in green, switch in blue).

Symmetrical switch cost was found for all participants taken together (L1: 48ms; L2 33ms) as indexed by a non-significant "condition" × "language" interaction [F(1,17)=1.47,.*ns*]. When looking into the two groups separately, the switch cost for both languages was symmetrical both in early (L1:50ms; L2:21ms) and late bilinguals (L1:46ms;

L2:46ms) as indexed by a non-significant "condition" × "language" × "group" interaction [F(1,17)=1.30,.*ns*, see figure 12].

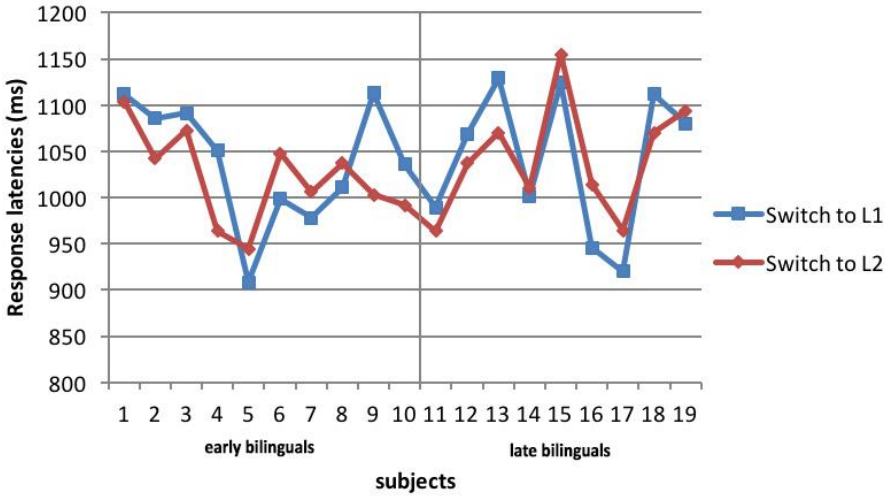

Figure 13. Participants' performance in the switch trials.

This figure illustrate performance for each participant for switching to L1 and to L2.

Figure 13 illustrates performance for each participant in the switch trials. In the early bilingual group, we observe that a participant has a larger mean difference between switch to L1 and switch to L2 (110ms) but similar performance in blocked condition (L1= 1031ms; L2: 1004ms). This explains the greater difference in early bilingual switch costs.

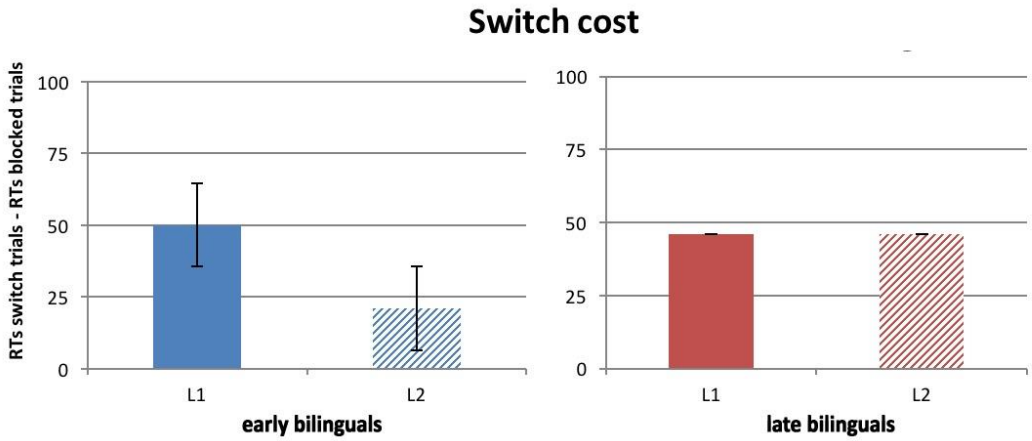

Figure 14. Mean switch cost in early and late bilinguals

This figure illustrates the magnitude of the switch cost for L1 and L2 for early bilinguals (left) and late bilinguals (right). Error bars represent the standard error.

Furthermore, we correlated the L1 switch cost with the index of L1-L2 balance. The index is the result of substraction of L2 proficiency from L1 proficiency. We found a positive correlation (r=0.478, n=19, p=0.03, see figure 15), meaning that the more dominant the L1 the greater the effort to switch to the L1.

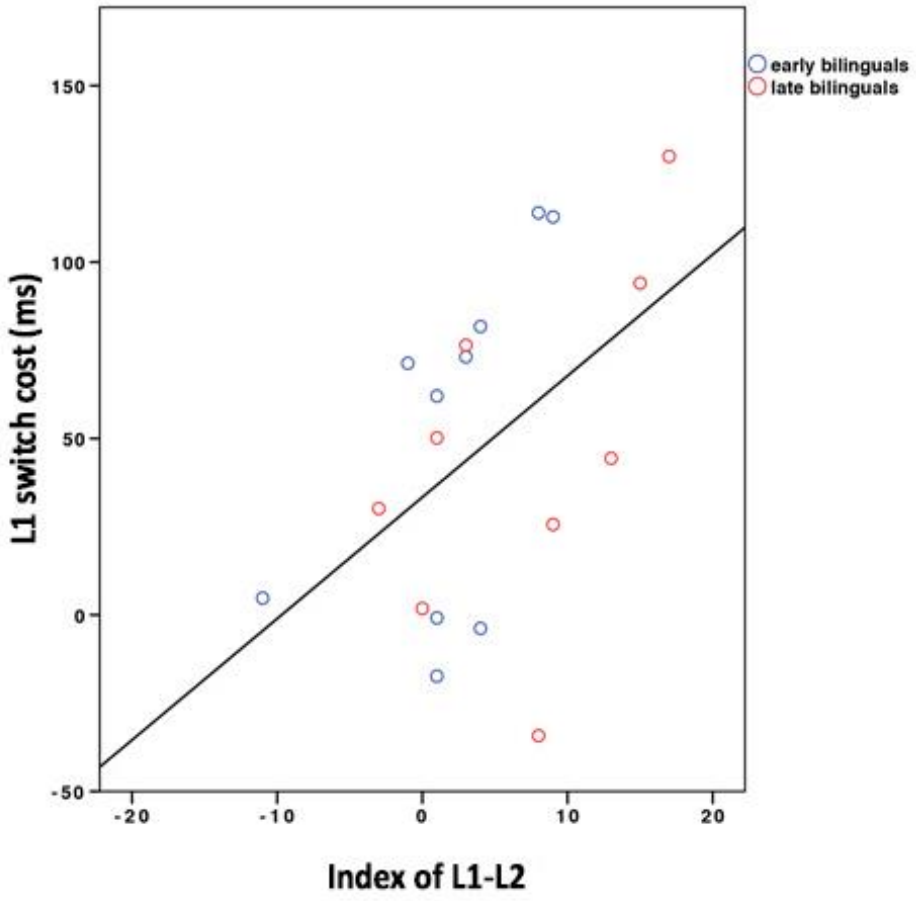

Figure 15. Correlation between L1 switch cost and the index of L1-L2 balance.

Scatter plot of the relationship between L1 switch cost (in ms) and the index of L1-L2 balance.

To summarize, performance on the picture naming task was similar between the two groups. No difference was found in RTs between the two groups. The early bilingual group showed higher variation in the switch costs but this can be explained by the performance of one participant. A positive correlation was observed between the index of L1-L2 and the switch to the L1.

3 Imaging results

3.1 Whole brain analyses

Overall participant's analyses: L1, L2, switch. A general analysis was conducted on the three picture naming conditions across all participants (early and late bilinguals, n=20, see figure 16) to investigate the brain areas activated in highly proficient bilinguals. Activation in **L1 and L2** compared to the baseline condition revealed similar bilateral activity in cortical areas of frontal and parietal lobes, however it was only in L2 picture naming that a left-lateralized neuronal activity was observed in inferior frontal gyrus (Broca's area; BA 44/45) and in the anterior insula was observed. Activity in the supplementary motor areas (medial BA 6) was more extended in the left hemisphere for both blocked conditions. Bilateral activity was present in the visual cortex (BA 17, 18, 19), the fusiform gyrus (BA 37), the dorsolateral premotor area (BA 6), the postcentral gyrus (BA 4), the superior parietal lobule (BA 7), the superior temporal cortex (BA 21/22), the posterior inferior temporal gyrus (BA 20), the anterior cingulate cortex (BA 32), and cerebellum. The activation of left thalamus was observed only in L1 naming.

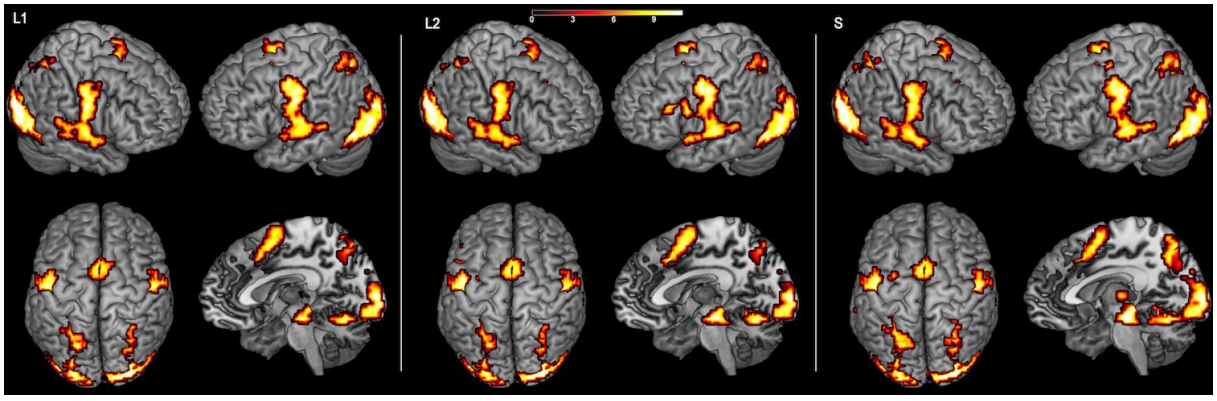

Figure 16. Activation of all participants for L1, L2 and switch condition.

Brain areas that show greater activation for L1, L2 and switch (S) naming compared to the baseline in early and late bilinguals (n=20) performing the picture naming task at p<0.05 corrected, k=100.

The **switch condition** compared to the baseline revealed a similar pattern of brain activity, namely the bilateral precentral gyrus (BA 6), the SMA and anterior cingulate cortex (BA 32), the superior temporal gyrus (BA 22), the posterior inferior temporal gyrus (BA 20),

the fusiform gyrus (BA 37) and the occipital lobe (BA 17, 18, 19), the thalamus and the cerebellum. Statistical tables of fMRI task results are showed in Annexe 3.

Direct comparison was conducted between each language and between **switch vs. blocked** condition taking into account all subjects within the two groups. The direct comparison between switch *vs.* blocked condition revealed increased activity in the bilateral inferior and superior parietal lobule (BA 40/7), the left precentral gyrus (BA 6), the left middle frontal gyrus, and middle cingulate cortex (BA 24/32; see figure 17 and table 10).

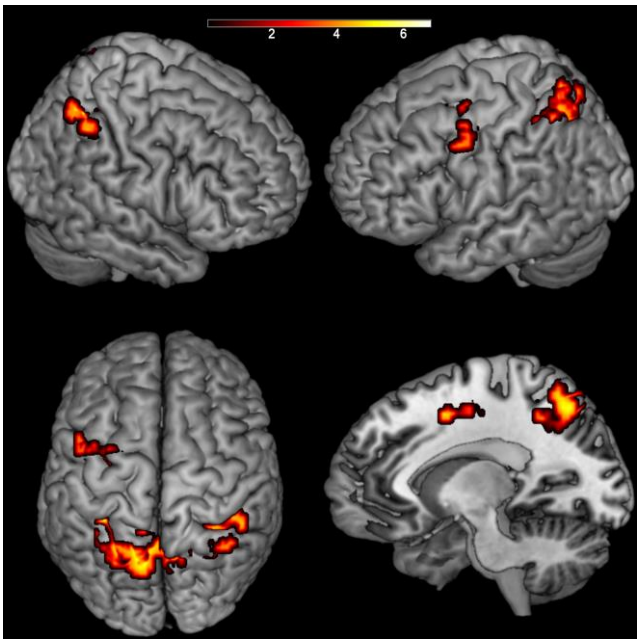

Figure 17. Activity of all participants during switch condition compared to blocked condition.

Brain areas that show greater activation for switch naming compared to the blocked condition in early and late bilinguals (n=20) performing the picture naming task at p<0.001 uncorrected, k=100

Table 10. Statistical tables of fMRI task: switch condition *vs* blocked condition.

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
L Inferior Parietal Lobule (BA 40)	376	6,802	-30	-46	47
L Precuneus (BA7)		6,462	-15	-58	53
R Precuneus (BA7)		5,627	6	-55	50
R Inferior Parietal Lobule (BA 40)	134	5,666	30	-49	47
L Middle Frontal Gyrus (BA 6)	129	5,484	-24	-7	47
L MCC (BA 24/32)		5,13	-12	5	47
L Precentral Gyrus (BA 6)		4,184	-48	5	44

Areas of increased activity for switch condition compared to blocked condition in proficient bilinguals (N=20).

Within-groups analyses: in this section, we will show the results of the three conditions for each group compared to the baseline (see Fig. 18).

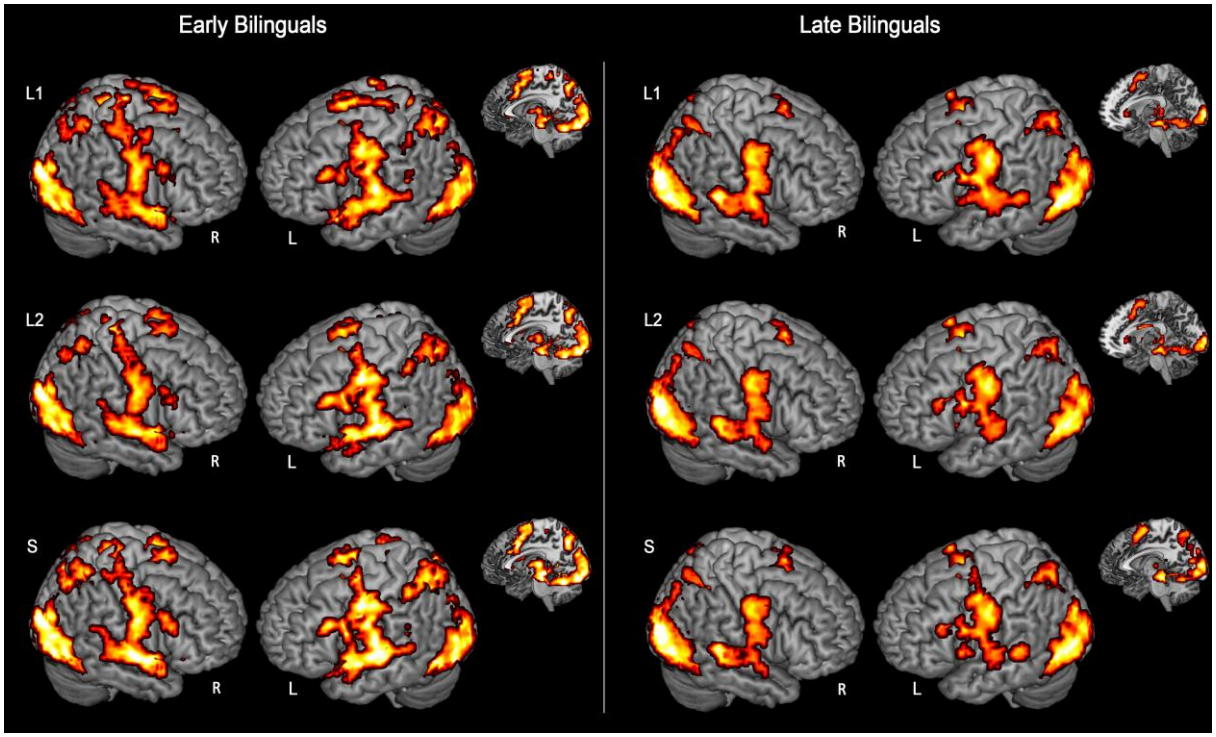

Figure 18. Brain activity of each group for L1, L2 and switch condition.

Brain areas that show greater activation in the left hemisphere for switch naming compared to the blocked condition (L1 and L2) and in the switch condition in early (n=10) and late bilinguals (n=10) performing the picture naming task at p<0.001 uncorrected, k=100.

Late bilinguals: activation was found at p=0.001 uncorrected, k=100. Similar activations were observed in late bilinguals in the three conditions. We observed activation of the bilateral precentral gyrus, superior and middle temporal gyrus, fusiform gyrus, supplementary motor area (medial BA), anterior cingulate cortex, precuneus, superior parietal lobe, culmen, thalamus (excepted in the switch condition) and the visual cortex. Left-lateralized neuronal activity was observed in the inferior frontal gyrus (44, 45), middle frontal gyrus (BA 9). Statistical tables of fMRI task results are showed in Annexe 5.

Early bilinguals: activation was found at p=0.001 uncorrected, k=100. Again, similar activations were observed in early bilinguals in the three conditions. We observed activation of the bilateral precentral gyrus, superior and middle temporal gyrus, fusiform gyrus,

supplementary motor area (medial BA), anterior cingulate cortex, precuneus, superior and inferior parietal lobe, culmen, thalamus and the visual cortex. Left-lateralized neuronal activity was observed in the anterior insula (bilaterally in the switch condition), the inferior frontal gyrus (44, 45) and the DLPFC (BA 9/47). Statistical tables of fMRI task results are showed in Annexe 4.

Between-group analyses. The direct comparison between early and late bilinguals did not reveal any differences in activation.

3.2 ROI analyses

We extracted the parameter estimates of the BOLD signal in the three regions of interest left ACC, left SMA and left DLPFC (BA9/46) during switch condition. No difference was found in the left ACC (Ts<1), left SMA (Ts<1), DLPFC (Ts<1; Fig. 19).

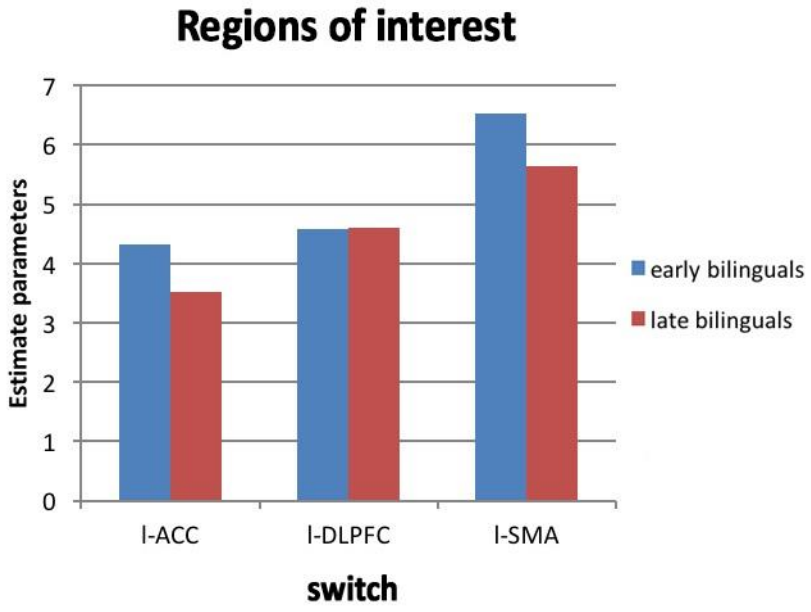

Figure 19. The mean parameter estimates of the BOLD effect in three ROI in switch condition.

The mean parameter estimates of the BOLD effect in the ACC-region of interest (peak coordinate: x = -3, y = 14, z = 38), DLPFC (peak coordinate: -45, y = 15, z = 25), SMA (peak coordinate: x = -3, y = 2, z = 59) in switch condition and switch vs blocked condition.

A negative correlation was found between the switch cost effect (measured as the difference between switch trials and blocked trials) and parameter estimates of the BOLD signal of the DLPFC (r=-0.669, n=19, p=0.002) and the SMA (r=-0.658, n=19, p=0.002; see figure 20) but not for the ACC during the switch condition (r=-0.415, n=19, *.ns*).

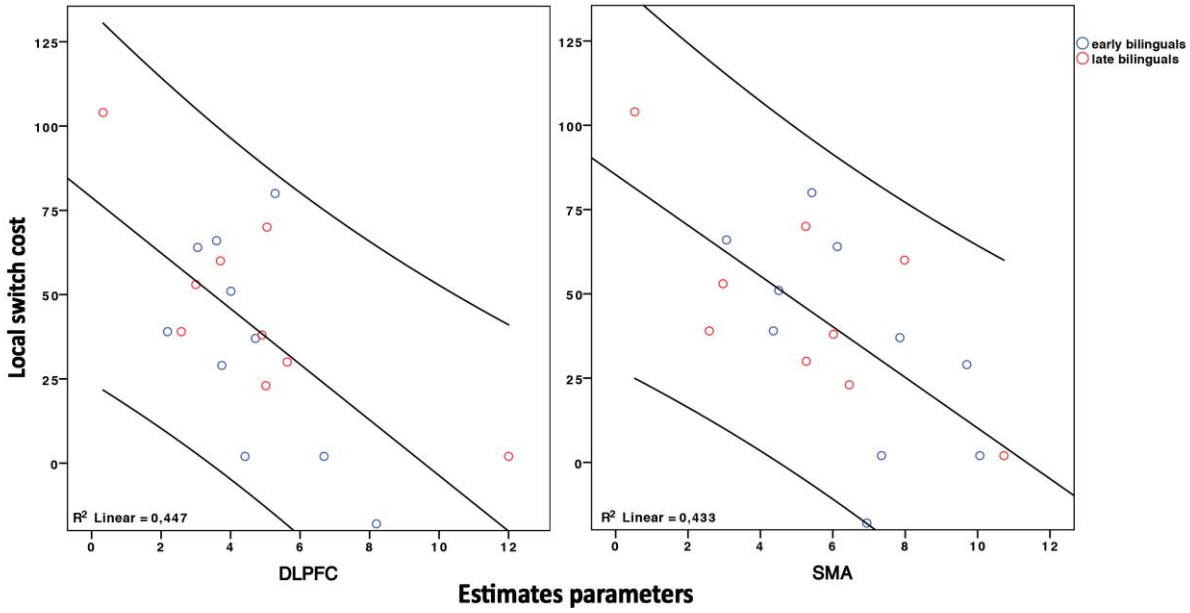

Figure 20. Correlation between switch cost and mean values for BOLD signal measuring fMRI activity.

Scatter plot (with mean and individual CIs) of the relationship between switch cost (in ms; (measured as the difference between switch trials and blocked trials) and mean values for BOLD signal measuring fMRI activity in the DLPFC (x = -45, y = 15, z = 25) and SMA (x = -3, y = 2, z = 59) in switch condition. Blue = early bilinguals; Red = late bilinguals.

3.3 Cortical thickness analyses

Cortical thickness contrasts of early bilinguals compared to late bilingual showed differences in two Brodmann areas. The area 45 right (Broca's area) was significantly thicker in early bilingual group (0.86mm) compare to late bilingual group [0.79mm; t(18)=-2.681,p=0.01]. The same pattern was found for area 38 left, the most rostral portion of the STG and the middle temporal gyrus, known as the temporal pole (early: 1.25mm; late 1.15mm, t(18)=2.103, p=0.05).

To summarize, the imaging data of the 20 bilinguals showed greater activation in the switch condition compared to blocked condition. A negative correlation was found between the switch cost and mean values for BOLD signal in the DLPFC and the SMA. Higher cortical thickness was found in early bilinguals in two regions involved in language processes, the right IFG (BA45) and the most rostral portion of the superior temporal gyrus (STG) and the middle temporal gyrus.

CHAPTER 6: DISCUSSION

The aim of this study was to elucidate the role of age of acquisition in two populations of bilinguals with equal level of language proficiency in both languages and executive function abilities (inhibition, working memory and cognitive flexibility). More precisely, we wanted to test whether early bilingualism has an influence on the bilingual brain. First of all, we discuss the results of the language assessment. Second, we discuss the neural correlates of early and late bilinguals in a picture naming task (as well as their correlations with behavioral measures). Lastly, we discuss the structural changes that learning a language early in life can lead to.

1 Bilingual individual's assessment

In chapter 3, we have exposed the issue of the assessment of spoken languages in psycholinguistic studies, and the need for characterizing the bilingual individual through the use of complementary approaches, ranging from sociolinguistic to educational background. In our study, in order to establish a portrait of the bilingual subject as rich as possible, we made our participants go through a large battery of language (test ELAO, verbal fluency task, picture naming task) and neuropsychological tests (MMSE, WAIS-digit span, Stroop test, TMT). The aim of these tests was to ensure that the two groups differed only in one factor, namely the age of acquisition, and also to give us the possibility to perform further analyses, for example correlating these results with the behavioural performance of our participants.

The main difference between both groups was that early simultaneous bilinguals had acquired both languages from birth, while the late sequential bilinguals had started learning the L2 at 10. Additionally, different AoA has repercussion of manner of acquisition. Simultaneous bilinguals acquired both languages at home and they were educated in their L1, while the late bilinguals had been exposed to their L1 and L2 in a school setting. This was made evident by the self-reported language measures. The only significant difference found in the language assessment tests of the two groups was in the writing subtest of the L2 self-evaluation. Early bilinguals declare to have a lower ability in writing than late bilinguals.

Beside the fact that language assessment in both languages was necessary to assure the *homogeneity* (except for the AoA) of the two groups, we found that the index of L1-L2 balance was positively correlated with the switch cost to the L1. In other words, the bigger the

difference between L1 and L2 is, the more effort is needed to switch to L1. This result can be interpreted in terms of inhibition: Meuter and Allport (1999) claim that the magnitude of the inhibition applied to two languages is dependent of the relative strength of the two languages. A greater switch cost is present when switching from the less dominant language to the more dominant language because more inhibition is needed to inhibit the dominant language and, for this reason, it is more effortful to reactivate this language.

To sum up, our two groups have been matched for language proficiency in order to isolate the relevant factor, age of acquisition. Even if a very high proficiency was observed for all participants, we were able to reveal the relation between language dominance and the resulting magnitude of the inhibition needed to successfully switch, even in these highly proficient bilinguals.

2 fMRI analyses

2.1 Representation of two languages

One of the main goals of this study was to investigate the relationship between language representation and AoA in bilinguals who achieved a high level of proficiency in both languages. Functional neuroimaging research has found that L2 learners engage additional brain activity, mostly in the prefrontal areas that are more anterior to the classical language areas (De Bleser et al., 2003; Vingerhoets et al., 2003), whereas similar activations in the left frontal and temporo-parietal areas were observed when the degree of L2 proficiency is comparable to L1 (Hernandez et al., 2001, 2000; Klein, Zatorre, Milner, Meyer, & Evans, 1994). These findings are in line with the convergence hypothesis positing that the neural representation of the L2 converges with the one of L1 once high proficiency is reached (Green, 2003). Furthermore, to our knowledge, few studies have compared directly early highly proficient bilinguals and late highly proficient bilingual. This sort of comparison provides a critical test of whether the processing of L2 words depends on the age of acquisition of L2. Moreover, studies that did compare early versus late bilinguals did not observe similar results (Bloch et al., 2009; Chee, Caplan, et al., 1999; Isel, Baumgaertner,

Thrän, Meisel, & Büchel, 2010; Mahendra et al., 2003; Verhoef et al., 2009; Wartenburger et al., 2003; Wattendorf et al., 2012), therefore studies that compare these two kinds of population are still required.

Our study integrates the debate of the "*optimum biological moment*" (Locke, 1997) assuming that the mental representation of a late L2 lexicon is affected by neural maturation, suggesting a difference between early L2 and late L2 mental lexicon representation and trying to contribute to the knowledge of the neural representation of languages of highly proficient bilinguals, i.e. whether the representation of two languages in late highly proficient bilinguals converge or not.

At the behavioural level, our results showed a significant difference in terms of errors only when both groups were analysed together: more errors were made during L2 naming compared to L1. It is known that when a bilingual intends to speak one language, alternatives in both languages are activated (Costa et al., 1999; Hermans et al., 1998; Kroll, Bobb, & Wodniecka, 2006) and for this reason, a higher rate of errors is expected in combination of higher response latencies when using the less dominant language. This effect has been interpreted as an effect of execution of a more difficult task due to the dominance of one language over another (Misra et al., 2012). But in our study, no difference was found in terms of response latencies and this result is consistent with the functional activations observed for naming in L1 and L2. Indeed, similar neural representations of the L1 and the L2 of late bilingual and between the L2s of early and late bilinguals were observed. The network observed for both groups has already been identified as a network involved in picture naming tasks (Indefrey, 2011). All these regions involved, including posterior IFG, the posterior parts of the STG, the SMA, the fusiform gyrus and the cerebellum, have been related to word production (Indefrey, 2011). Activity in precentral and postcentral gyri areas has been related to articulatory processing (Hillis et al., 2004) and are assumed to reflect the retrieval of stored phonological representations in overt naming (Murtha, Chertkow, Beauregard, & Evans, 1999). The superior parietal lobule has been related to semantic processing (Wong, Yin, & O'Brien, 2016).

Since no difference was found between naming in the L1 and the L2, our results reinforce the hypothesis according to which the representations of two languages converge once highly proficiency is reached in both languages. Other functional neuroimaging studies have reported similar activations in frontal and temporoparietal areas in balanced bilingual speakers (Chee, Tan, et al., 1999; Hernandez et al., 2001, 2000; Perani et al., 2003). In

conclusion, it seems that proficiency, rather than age of acquisition, exerts a more important influence on language representations. As L2 develops in a context in which the L1 system is already specified, it is plausible to think that L2 will be processed through the same neural network of L1. Therefore, a highly proficient L2 is processed in a more automatic fashion as a native-like language, leading to the disappearance of the activation of the prefrontal areas related to cognitive control and similar language representations.

To summarize, our results suggest that once native-like proficiency is achieved, the neural representation of the L2 converges with that of the L1 (D. W. Green, 2003; Perani & Abutalebi, 2005). Since the production of each lexical item is more practiced, the between-language competition can be resolved more automatically and will demand less cognitive effort. With regard to neural activity, training results in specific changes in task-related brain activity with decreased activity after training (Erickson et al., 2006). Hence, naming in the L1 or in the L2 will demand less need of control mechanism that will be translated by decreases of activation of the anterior regions in the prefrontal cortex (BA 9, BA 46 and BA 47) that are related to cognitive control. This is what we observed in both within group and between group comparisons.

2.2 Language cognitive control

The second goal of this study was to study the role of AoA in bilinguals in a switch condition. Behavioural data showed a difference between blocked and mixed naming. In the mixed context, responses were slower and less accurate. These findings are in line with previous studies which showed a language context effect and suggest a language switch cost when alternating between two languages (Costa & Santesteban, 2004). It is also interesting to observe the magnitude of the switch cost, which varies depending on the difficulty of the task. For instance, switching from the non-dominant to the dominant language entails larger switch costs due to stronger inhibition of the dominant language when processing the non-dominant (Meuter & Allport, 1999). This pattern is not observed in highly proficient bilinguals due to the lack of difference in proficiency between the two languages. Hence, the amount of inhibition needed to inhibit one language or the other is equivalent. But other studies have observed a symmetric switching cost in highly proficient bilingual speakers even when they were switching to a third low-proficient language (Costa et al., 2006) or in unbalanced

bilinguals in voluntary switch task (e.g. Gollan & Ferreira, 2009), or when there is an extended interval in which to prepare for the switch (e.g. Verhoef, Roelofs, & Chwilla, 2009). Such results are challenging for the Inhibitory Control model, because an asymmetric switch cost is expected when switching from a low-proficient language to the more proficient one due to stronger needs of inhibition. In order to explain such results, it has been suggested that once a certain level of proficiency is attained in two languages, a mechanism specific to language control, not relying on domain-general inhibition, is used to overcome lexical competition in the target language (Calabria et al., 2012; Christoffels, Firk, & Schiller, 2007).

Moreover, it has been said that few bilinguals are truly balanced, and even when high proficiency is achieved, late bilinguals remain dominant in one language, i.e. L1 (Misra et al., 2012). Hence, even if symmetrical switch cost is observed, naming in L1 is often slower than in L2, suggesting that the L1 is indeed inhibited under mixed language condition (Kroll, Bobb, Misra, & Guo, 2008). Our results seem to show the opposite. No behavioural difference was found between the two groups and a symmetrical switch cost was observed suggesting, not only, that early and late bilinguals can achieve the same level in language proficiency and ability in language control, but also that late bilinguals can be truly balanced.

To summarise, in our study, we did not find any asymmetrical switch cost, even in the late bilingual group, allowing us to affirm that even if a language is learned later in life, a native-like level can be reached. But we cannot examine the existence of a language specific mechanism, since our participants were not trilingual.

At the brain level, switch condition, compared to blocked condition, revealed increased activity in a network, including left precentral gyrus, the middle frontal gyrus, the anterior cingulate cortex and the bilateral precuneus and the inferior parietal lobules. This pattern of activation has been already identified as areas being part of a network involved in cognitive control, and more precisely in inhibition mechanisms (Wager et al., 2005).

The left prefrontal cortex (PFC) and the ACC are two regions that play a predominant role in cognitive control. In particular activation of the dorsolateral prefrontal cortex has been reported on tasks in which selection of the target stimulus is required for overcoming the preponderant irrelevant response (Heidlmayr, Doré-Mazars, Aparicio, & Isel, 2016; Hernandez, 2009; Khateb et al., 2007; Wang et al., 2009) and the anterior cingulate cortex is a crucial region associated with error detection and conflict monitoring. Previous studies observed that these two regions are co-activated in conflict tasks and play a crucial role in the selection of different response alternatives, task switching, maintaining a stable representation

of the current task and inhibiting irrelevant items held in working memory (Rodriguez-Fornells, De Diego Balaguer, & Münte, 2006). Studies have tried to dissociate their roles: the ACC seems to be responsible for evaluating the demand of cognitive control and of the transmission of the need of greater control to the prefrontal cortex. The inferior and superior parietal lobules have been related to language selection in studies on language control (Abutalebi & Green, 2007; Hernandez, 2009) and to distinct executive functions as inhibition, flexibility and working memory (Niendam et al., 2012). Activation of the precuneus has been found in other language switching studies (Guo, Liu, Misra, & Kroll, 2011; Wang et al., 2007) and has been linked to response inhibition (Bunge et al., 2002) but its precise role has not been clarified (de Bruin et al., 2014).

Moreover, in our study further analysis showed that higher activity in the DLPFC and the SMA in the switch context was correlated with a lower local switch cost. Given that DLPFC and SMA are crucially involved in language control and in language switching tasks (Abutalebi & Green, 2016), these results suggest that highly proficient bilinguals that "tune up" these regions, make them more efficient in handling conflict. More activity in the PFC has already been associated with better performance in individuals with good control abilities (Bialystok, Craik, et al., 2005; Garbin et al., 2010).

To summarise, the results of this experiment revealed that highly proficient bilingual speakers did not show significant differences depending on age of acquisition of their language, and furthermore, they did not show asymmetrical switch cost either, suggesting that proficiency, rather than AoA, affects the way bilinguals control their speech. Moreover, switching between languages in highly proficient bilinguals involves an increase in areas reported as components associated with inhibitory processes, suggesting that language switching recruits a neural network that is engaged for domain-general executive control functions rather than a specific language system. Still, in highly proficient bilinguals relative higher activity in areas involved in language control, namely the DLPFC and the SMA, result in better performance.

3 Brain plasticity

In this study, we also investigated the effect of learning a L2 on the structure of the brain. The investigation of the relationship between learning a L2 and the modification of the brain are still exploratory. Studies of individuals, who differ in terms of L2 AoA, can shed light on the influence of variation in early language experience on the shaping of the brain structure. Several studies carried out in healthy adults have revealed that bilinguals relative to monolinguals differ in terms of increased gray or white matter density in brain areas such as the left inferior frontal gyrus (Stein et al., 2012), left inferior parietal lobule (Della Rosa et al., 2013; Mechelli et al., 2004), left anterior temporal pole (Abutalebi et al., 2014), the anterior cingulate cortex (Abutalebi et al., 2012), and in subcortical structures such as the left caudate (Zou, Ding, Abutalebi, Shu, & Peng, 2012) and the putamen (Abutalebi, Della Rosa, Castro Gonzaga, et al., 2013)

In this study we expected to find higher thickness in the cortices in simultaneous bilinguals given their early language experience in areas associated with language. Our results showed that simultaneous bilinguals display thicker right IFG than late bilinguals. These findings were observed also in Klein et al. (2014) and provide evidence that the AoA shapes the structure of the brain. The changes in the inferior frontal cortex in our study might reflect different learning processes associated with implicit and explicit language learning. Our evidence is consistent with the findings of Hull and Vaid (2007) that showed that bilinguals who acquired both languages by six years of age showed involvement of both hemispheres for both languages, whereas those who acquired their second language after age six showed left hemisphere dominance for both languages.

Moreover, our study indicates specific plastic effects associated with L2 age of acquisition in the left temporal pole: thicker cortex in early bilinguals than in late bilinguals. This region has already found to be thicker in bilinguals compared to monolinguals in the study of Abutalebi and colleagues (2014). And it is known to be involved in the storage of lexical concepts and in the separation of these lexical concepts in two languages in order to guide speech production and comprehension processes (Abutalebi et al., 2014). Our interpretation is that this structure is a potential target for plastic changes in early bilingual individuals, because it must be recruited to guide word production in each language of the bilingual speaker since birth.

4 Limitations

Results and conclusions discussed come along with some limitations. Firstly, a small sample of participants for each group (=10) could be recruited. In the future, a larger sample should be enrolled in order to affirm with more assurance evidence observed in this study. Moreover, the mother tongue of the participants could be either English or French, even though the repartition was quite balanced in the two groups (see table 3). Additionally, due to material limitation, the neuropsychological assessment was only performed in French, but no participant expresses discomfort in using French and all participants, but one (an early bilingual) was living in France at the moment and speaking French every day for work or academic purpose. In addition, even if all participants declared to speak English very often, Toulouse has not a bilingual society as Barcelona and Montréal; hence it is plausible that French was the language more used on a daily basis.

As regards to the fMRI study, larger blocks of "activations" and "baseline" should be used, in order to allow the haemodynamic response to achieve the maximum level during the activation blocks and the base level during the rest. Furthermore, an event related paradigm could allow us to disentangle the "switch condition" and investigate the haemodynamic response of the switch to L1 and the switch to L2.

CONCLUSION AND PERSPECTIVES

The aim of the present study was to investigate two populations of bilinguals with specific attention to the characterization of the bilingual speaker. Earlier studies on bilingualism paid little attention to the assessment of L1, SES, manner of L2 acquisition and that explains the inconsistent results between studies. In our study, we tried to create a complete portrait of the bilingual speaker using various assessments in order to assure the homogeneity of the two bilingual groups, early and late bilinguals.

Our study modestly tries to integrate the debate about the relation between human language faculty and human neural maturation. The direct comparison of early simultaneous and late bilinguals is the most suitable way to disentangle the effects of learning two languages from birth or a second one later in life. The present study did not reveal an effect of early age of acquisition on brain language representation and in that way, it clarifies the role of age of acquisition and proficiency. Even if the earlier we start the easiest we learn a language, it appears that late bilinguals can achieve a native-like level of proficiency in L2 and behave as early bilinguals. These results sustain the idea supported by the Convergence hypothesis (D. W. Green, Crinion, & Price, 2006) in that once high proficiency is achieved in the second language, the representation of this language converges to the representation of the mother tongue. However, as shown by the morphometric data, we could find a signature of early bilingualism in the structure of the brain supporting the idea that native-like exposure to a second language (implicit learning) impacts second language learning and structural brain changes. More studies need to be realized in order to investigate how early life experience of a language leaves its marks on brain structure and function. Recently, studies on bilingualism have started to investigate the resting-state connectivity in different bilingual populations in order to determine the functional connections between separated brain areas at rest (Berken, Chai, Chen, Gracco, & Klein, 2016).

As regards bilingual language control, behavioural data and functional imaging data point in the direction of proficiency playing a more important role than age of acquisition. Our two groups resulted to behave in the same way. We could not find an asymmetrical switch cost or greater activity in the late bilingual group as one could expect, supporting the idea that high level of proficiency can be reached in the L2 even when the second language is

learned later. Consequently, switching from the L2 to the L1 did not entail additional resources in either early or late bilinguals. Even if we could not find any functional difference related to age of acquisition, our study showed that in individuals with high level of proficiency, higher activity in the PFC is linked to behavioural facilitation in a switch task. These findings confirm the crucial role of this region in language control and suggest that the way an individual can “tune up” this area affects the way bilinguals control their speech. Nevertheless, in order to bring a clear answer to the debate about the existence or not of a specific control mechanism of languages, it will be indispensable in the future to compare early and late bilinguals performing tasks in which neural correlates of task switching and language switching can be directly compared.

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ANNEXES

Annexe 1. Sociolinguistic questionnaire

Questionnaire sociolinguistique

Numéro d'identification : ……

Date :

Date de naissance ...../...../.....

2. Vous êtes ❑Homme ❑Femme

3. Où êtes-vous né ?
Ville.....

Département.....

Pays.....

4. Quelle nationalité avez-vous ? ❑Française ❑Autre……

5. Quel est votre niveau d'étude ?
- ❑École primaire
- ❑Collège
- ❑Lycée
- ❑Baccalaureat + 1
- ❑Baccalaureat + 2
- ❑Baccalaureat + 3
- ❑Baccalaureat + 4
- ❑Baccalaureat + 5
- ❑Baccalaureat + 8
- ❑Autres parcours et remarques:

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6. Quelle est votre profession ? Si vous êtes à la retraite, merci d'indiquer votre dernière profession :
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.....
.....

7. Si vous avez eu différentes professions, merci de les indiquer dans l'ordre chronologique.
1.....de.....à.....
2.....de.....à.....
3.....de.....à.....
4.....de.....à.....

8. Avez-vous toujours habité en France ? ❑Oui ❑Non

Si non, où ? Et pour combien de temps ?
.....

9. Avez-vous habité dans un pays Anglophone ? ❑Oui ❑Non

Si oui, où ? Et pour combien de temps ?
.....

10. Quelle est la langue maternelle de vos parents ? Et quelle langue utilisent-ils à la maison avec vous ?

Mère...../.....
.....

Père...../.....
.....

11. Avez-vous déjà passé une période supérieure à 3 mois dans un pays Anglophone ?

❑Oui ❑Non

12. Si oui : Combien de fois ?
.....

Où ?
.....

Pour combien de temps ?
.....

Pour quelle raison ? ❑Études ❑Travail ❑ Autre.....

À quelle âge ?
.....

13. Allez-vous régulièrement dans un pays anglophone ?

❑Plus de trois fois par an
❑Deux ou trois fois par an
❑Une fois par an
❑Une fois tous les deux ou trois ans
❑Moins d'une fois tous les trois ans
❑Jamais

14. Quelles langues avez-vous apprises avant l'école ?

❑Français ❑Anglais ❑ Autres.....

15. Quelles langues avez-vous apprises en classe ?

❑Français ❑Anglais ❑ Autres.....

16. Et pour combien d'années ?

Français.....
Anglais.....

Langue 3.....
Langue 4…….

17. À quelle âge ?
Français.....
Anglais.....
Langue 3.....
Langue 4……

18. Avec quelle fréquence par semaine ?
Français.....
Anglais.....
Langue 3.....
Langue 4……

19. Avez-vous appris une langue hors du contexte scolaire ?
❑Oui, laquelle..... ❑Non

20. De manière générale, comment qualifieriez-vous votre niveau de français ? Sur une échelle de 1 à 6. 1 = très mauvais niveau, 6 = niveau équivalent à un francophone natif.
1 2 3 4 5 6

21. De manière plus détaillée, comment considérez-vous votre niveau de français dans les quatre situations qui vont suivre? Sur une échelle de 1 à 6 :
1= très difficilement, 6= sans aucun effort

Je parle :
1 2 3 4 5 6

Je comprends :
1 2 3 4 5 6

J'écris :
1 2 3 4 5 6

Je lis :
1 2 3 4 5 6

22. De manière générale, comment qualifieriez-vous votre niveau d'anglais ? Sur une échelle de 1 à 6. 1 = très mauvais niveau, 6 = niveau équivalent à un anglophone natif.
1 2 3 4 5 6

23. De manière plus détaillée, comment considérez vous votre niveau d'anglais dans les quatre situations qui vont suivre? Sur une échelle de 1 à 6 :
1= très difficilement, 6= sans aucun effort

Je parle :
1 2 3 4 5 6

Je comprends :
1 2 3 4 5 6

J'écris :
1 2 3 4 5 6

Je lis :
1 2 3 4 5 6

24. Croyez-vous avoir le même niveau en français et en anglais ?
❑Non, je suis plus compétent en français
❑Oui
❑Non, je suis plus compétent en anglais
❑Je ne sais pas, parce que.....

25. Avec quelle fréquence parlez-vous français ?
❑ rarement ❑ quelque fois par an ❑ mensuellement ❑ chaque semaine ❑ quotidiennement

26. Avec quelle fréquence parlez-vous anglais ?
❑ rarement ❑ quelque fois par an ❑ mensuellement ❑ chaque semaine ❑ quotidiennement

27. Êtes-vous plus à l'aise en parlant français ou anglais ?
❑Français ❑Anglais ❑Pas de préférence

28. Croyez-vous important de maintenir votre niveau en L2 ? (❑anglais ❑français)
❑non important
❑peu important
❑assez important
❑important
❑très important

29. Avez-vous l'opportunité de parler votre L2 avec des personnes de langue maternelle ?
❑ Oui, avec quelle fréquence ?.....
❑Non

30. Dans quelle langue parlez-vous maintenant à la maison ?
❑Français ❑Anglais ❑Les deux ❑Autre.....

31. Quelle est votre situation familiale ?
❑Marié/Pacsé ❑Séparé/Divorcé ❑Veuf/Veuve ❑En couple ❑ Célibataire

Si vous êtes célibataire, passez directement à la question n. 36.

32. De quelle nationalité est votre conjoint ?
❑ Français ❑ Autre

33. Quelle est la profession de votre conjoint ?
.....

34. Dans quelle langue parlez-vous généralement avec votre conjoint ?
❑ Seulement français
❑ Seulement anglais
❑ Français et anglais sans préférences
❑ Français et anglais mais généralement français
❑ Français et anglais mais généralement anglais
❑ Autre

35. Dans quelle langue contre conjoint généralement parle avec vous ?
❑ Seulement français
❑ Seulement anglais
❑ Français et anglais sans préférences
❑ Français et anglais mais généralement français
❑ Français et anglais mais généralement anglais
❑ Autre

36. Avez-vous des enfants ?
❑ Non ❑ Oui, combien.....
Si la réponse est NON, passez à la question n. 40.

37. Quel âge ont-ils ?
.....

38. Dans quelle langue parlez-vous avec lui/eux ?
❑ Seulement français
❑ Seulement anglais
❑ Français et anglais sans préférences
❑ Français et anglais mais généralement français
❑ Français et anglais mais généralement anglais
❑ Autre

39. Dans quelle langue votre/vos enfant(e)(s) vous parlent ?
❑ Seulement français
❑ Seulement anglais
❑ Français et anglais sans préférences
❑ Français et anglais mais généralement français

❑ Français et anglais mais généralement anglais
❑ Autre

40. Pouvez-vous indiquer dans le tableau suivant en quelle mesure vous utilisez le français (table1) ou l'anglais (table2) dans les domaines fournis ?

Je parle français...					
	Tout le temps	Fréquemment	Parfois	Rarement	Jamais
Avec ma famille					
Avec mes amis					
Avec mes animaux					
Au travail					
Dans un contexte scolaire ou universitaire					
Dans des associations					

Je parle anglais...					
	Tout le temps	Fréquemment	Parfois	Rarement	Jamais
Avec ma famille					
Avec mes amis					

Je parle anglais...					
Avec mes animaux					
Au travail					
Dans un contexte scolaire ou universitaire					
Dans des associations					

41. Écoutez-vous la radio française Sur une échelle de 1 à 6
1= jamais
6= tout le temps
1 2 3 4 5 6

42. Écoutez-vous la radio anglaise ? Sur une échelle de 1 à 6
1= jamais
6= tout le temps
1 2 3 4 5 6

43. Regardez-vous des programmes de télévision français ? Sur une échelle de 1 à 6
1= jamais
6= tout le temps
1 2 3 4 5 6

44. Regardez-vous des programmes télévision anglais ? Sur une échelle de 1 à 6
1= jamais
6= tout le temps
1 2 3 4 5 6

45. Lisez-vous des livres, des journaux ou des magazines français ? Sur une échelle de 1 à 6
1= jamais
6= tout le temps
1 2 3 4 5 6

46. Lisez-vous des livres, des journaux ou des magazines anglais ? Sur une échelle de 1 à 6
1= jamais
6= tout le temps
1 2 3 4 5 6

47. Vous arrive-t-il de passer du français à l'anglais et inversement dans votre vie quotidienne ?

❑Non ❑Oui

48. Lorsque vous devez passer du français à l'anglais. Comment le changement s'effectue-t-il ?

Sur une échelle de 1 à 6. 1= très difficilement, 6= sans aucun effort

1 2 3 4 5 6

49. Lorsque vous devez passer de l'anglais au français. Comment le changement s'effectue-t-il ?

Sur une échelle de 1 à 6. 1= très difficilement, 6= sans aucun effort

1 2 3 4 5 6

50. Parlez-vous parfois le français et l'anglais avec une même personne ?

❑ Non ❑Oui

51. Qui sont ces personnes (conjoint, enfants, amis, etc.)?

.....
.....
.....

52. S'il vous arrive de mélanger le français et l'anglais, le faites-vous?

❑Volontairement, si je ne trouve pas un mot
❑Involontairement
❑Les deux
❑Je ne sais pas

Vous arrivez à la fin de ce questionnaire. Vous pouvez ajouter des remarques concernant un point qui vous semble important. Ces remarques peuvent concerner votre vie personnelle, votre rapport à la langue/aux langues. Vous pouvez d'autre part faire des remarques sur le questionnaire en lui-même afin de pouvoir l'améliorer dans le futur.

.....
.....
.....
.....
.....
.....
.....

Annexe 2. Stimuli of the fMRI task and outcomes.

N. Stimulus	English	Alternative naming outcomes	French	Alternative naming outcomes
1	acorn	nut (5)	gland	noisette (6), noix (1)
2	anchor	hook (1)	ancre	
3	ant	spider (1)	fourmi	araignée (2)
4	anvil	weight (1)	enclume	poids (2)
5	apple		pomme	
6	arm		bras	
7	arrow		flèche	
8	barrel		tonneau	barrique (2), bidon (1)
9	basket	bag (1)	panier	
10	bear		ours	
11	bed		lit	
12	bee	fly (6), wasp (6)	abeille	mouche (3), guêpe (1), frelon (1)
13	bell		cloche	
14	belt		ceinture	
15	bench	pew (1)	banc	
16	binoculars		jumelles	binocle (1)
17	bird		oiseau	
18	bone		os	
19	book		livre	bouquin (1)
20	bow	bow tie (3), tie (2)	nœud	nœud papillon (7), ruban (1)
21	box	cardboard (1)	boîte	carton (7)
22	brain		cerveau	
23	bridge		pont	
24	broom		balai	serpillère (1)
25	butter		beurre	
26	cake		gâteau	
27	candle		bougie	
28	car		voiture	
29	castle		château	
30	cheese		fromage	gruyère (1)
31	church		église	
32	clock		horloge	
33	coat	jacket (9)	manteau	veste (1), chemise (1)
34	colander		passoire	écumoir (2), égouttier (1), entonnoir (1)
35	comb		peigne	
36	compass	scale (1)	boussole	horologe (1)
37	couch	sofa (17)	canapé	sofa (4)
38	cow		vache	
39	cup	mug (4), tea cup (4)	tasse	
40	dart	needle (1)	fléchette	flèche (2), dard (1)
41	deer		cerf	renne (2), chevreuil (1), cheval

				(1), biche (1)
42	desk		bureau	table (1)
43	dog		chien	
44	donkey		âne	
45	door	window (1)	porte	
46	drawer		tiroir	
47	dress		robe	
48	drum	tambourine (1)	tambour	batterie (1)
49	duck		canard	oiseau (1)
50	ear		oreille	
51	egg		œuf	
52	eye		oeil	
53	fan		ventilateur	air conditionnée (1)
54	faucet	tap (25), sink (1)	robinet	
55	feather		plume	feuille (1)
56	fence	barrier (2), bounderies (1)	haie	barrière (8), clôture (2), portail (1)
57	finger		doigt	
58	fish		poisson	
59	flag		drapeau	
60	fly	bee (5)	mouche	guêpe (1)
61	foot		pied	
62	fork		fourchette	
63	fox		renard	loup (2)
64	frog		grenouille	crapaud (1)
65	funnel		entonnoir	
66	ghost		fantôme	
67	glass	cup (1)	verre	
68	glasses		lunettes	
69	glove		gant	
70	goat		chèvre	bouc (2), brebis (1)
71	grapes		raisin	
72	gun	revolver (2), pistol (1)	pistolet	revolver (8)
73	hair		cheveux	
74	hammer		marteau	
75	hand		main	
76	hanger	cloth hanger (13)	cintre	porte manteau (1), épingle (1)
77	hat		chapeau	
78	cap	hat (8)	casquette	chapeau (9), béret (8)
79	heart		cœur	
80	helmet		casque	
81	hook		crochet	
82	horse		cheval	
83	house		maison	
84	key		clef	
85	king		roi	

86	knife		couteau	
87	ladder		échelle	éscalier (1)
88	ladle	spoon (4)	louche	cuillère (3)
89	leaf		feuille	
90	leg	knee (1)	jambe	pied (2)
91	lemon		citron	
92	lips	mouth (12)	lèvres	bouche (9)
93	lock	padlock (7), †locker (1)	cadenas	verrou (1)
94	lungs		poumons	
95	map		carte	mappemonde (2)
96	match		allumette	
97	monkey		singe	
98	moon		lune	
99	moose	deer (1), elk (2)	élan	caribou (9), renne (2), animal (1)
100	mop	broom (3)	serpillière	balai (12), éponge (1), nappe (1)
101	mouse	souris (5), rat (4)	souris	rat (2)
102	mushroom			champignon
103	nail		clou	
104	needle	match (1), pen (1)	aiguille	épingle (1)
105	nose		nez	
106	nut	bolt (4)	écrou	boulon (4), anneau (1), clou (1)
107	octopus		poulpe	pieuvre (11)
108	owl		hibou	choutte (8)
109	pants	trousers (12), jean (1)	pantalon	
110	pen	pencil (5)	stylo	
111	pencil	pen (8)	crayon	
112	picture	painting (13), photo (1), panel (1), art (1), board (1), paint (1)	tableau	peinture (7)
113	pig		cochon	
114	plate		assiette	
115	plug		prise	
116	pot	pan (7)	casserole	seau (1)
117	pumpkin		citrouille	potiron (1)
118	purse	bag (30), handbag (5)	sac	sac à main (3)
119	queen		reine	bouffon (1), roi (1)
120	rabbit		lapin	
121	rake		rateau	
122	ring		bague	anneau (2)
123	rocket		fusée	
124	roof		toit	
125	rooster	cockerel (5), chicken (4), hen (3)	coq	poulet (5)
126	rope		corde	
127	ruler		règle	
128	saddle		selle	
129	saw		scie	
130	scale		balance	

131	scarf		écharpe	
132	scissors		ciseau	
133	screw		vis	clou (6)
134	seal	phoque (1), sea lion (2), whale (1),morse (1)	phoque	lion de mer (2)
135	shark	whale (1)	requin	baleine (3)
136	sheep		mouton	
137	shell		coquillage	caillou (1)
138	shoe		chaussure	
139	skull		crâne	tête de mort (2)
140	skunk	squirrel (2), racoon (2)	moufette	putois (15), furet (2), blaireau (1)
141	snail		escargot	
142	snake		serpent	
143	sock		chaussette	
144	spider		araignée	
145	spoon		cuillère	
146	squirrel		écureuil	
147	stairs	staircase (5)	escalier	
148	star		étoile	
149	stool	chair (2), seat (1)	tabouret	
150	sun		soleil	
151	swan	goose (1)	cygne	oiseau (1)
152	swing		balançoire	
153	thumb		pouce	doigt (1)
154	tie		cravate	
155	tree		arbre	
156	truck	lorry (5)	camion	
157	turkey	bird (2)	dindon	dinde (12), paon (2), oiseau (1)
158	walrus	sea lion (6), seal (3), whale (1)	morse	
159	watch	clock (1)	montre	phoque (6)
160	well	water well (1)	puits	
161	whale		baleine	cheveux (5)
162	wheel		roue	
163	whistle		sifflet	
164	wig	hair (12)	perruque	
165	window		fenêtre	
166	wing		aile	
167	witch		sorcière	
168	wolf		loup	

Annexe 3. Statistical tables of fMRI task results for all 20 participants.

Results of the contrast «L1>baseline» (p<.05, FEW corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus (BA 19/18)	3047	17,318	27	-91	8
L Fusiform Gyrus (BA 37)		14,016	-39	-40	-16
L Middle Occipital Gyrus (BA 19/18)		13,777	-45	-67	-7
L Thalamus	267	12,450	-24	-34	8
L Putamen		7,367	-18	-7	8
L Precentral Gyrus (BA 6)	440	12,110	-48	-10	32
L Postcentral Gyrus (BA 4)		10,621	-57	-13	14
L Superior Temporal Gyrus (BA 22)		7,978	-60	-37	8
R Precentral Gyrus (BA 6)	389	11,864	54	-10	26
R Superior Temporal Gyrus (BA 22)		10,412	63	-7	2
		8,762	54	-34	8
L SMA (BA 6)	201	10,384	-3	5	56
R MCC (BA 32)		9,853	9	17	44

Results of the contrast «L2>baseline» (p<.05, FEW corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus (BA 19/18)	3012	18,713	27	-91	8
R Fusiform Gyrus (BA 37)		15,323	36	-64	-13
L Fusiform Gyrus (BA 37)		14,592	-39	-40	-16
L Insula Lobe (BA 13)	100	13,537	-33	14	2
		10,59	-27	29	-1
L Precentral Gyrus (BA 6)	451	12,266	-45	-4	47
L Superior Temporal Gyrus (BA 22)		11,300	-54	-16	5
L Postcentral Gyrus (BA 4)		8,783	-48	-7	23
R Precentral Gyrus (BA 6)	223	11,370	45	-13	35
R Postcentral Gyrus (BA 43)		9,502	63	-7	20
R Precentral Gyrus (BA 6)		6,740	48	2	50
L IFG (p. Opercularis) (BA 44)	108	11,109	-51	11	23
L Insula Lobe (BA 13)		9,116	-30	8	20
L SMA (BA 6)	243	10,896	-3	5	56
R MCC (BA 32)		9,650	9	17	44
L MCC (BA 32)		7,463	-9	20	32
R Superior Temporal Gyrus (BA 22)	164	9,831	60	-25	5
R Middle Temporal Gyrus (BA 21)		8,173	60	-1	-4

Results of the contrast «switch>baseline» (p<.05, FEW corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus (BA 19/18)	3317	18,018	27	-91	8
R Fusiform Gyrus (BA 37)		14,861	36	-61	-13
L Cuneus (BA 17)		14,703	-12	-97	-7
L Precentral Gyrus (BA 6)	455	12,234	-45	-13	32
L Superior Temporal Gyrus (BA 22)		11,637	-54	-16	5
		8,863	-60	-37	8
R Precentral Gyrus (BA 6)	391	11,951	54	-10	26
R Superior Temporal Gyrus (BA 22)		10,991	63	-7	2
		8,814	51	-34	8
L SMA (BA 6)	230	10,034	-3	2	59
R MCC (BA 32)		8,811	9	17	44

Annexe 4 Statistical tables of fMRI task results for early bilinguals.

Results of the contrast «L1 >baseline» (p<.001, no corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
L Postcentral Gyrus	6873	18,476	-57	-13	14
R Middle Occipital Gyrus	6873	17,592	24	-94	11
R Hippocampus	6873	16,051	30	-34	-1
R Postcentral Gyrus (BA3)	236	12,495	9	-34	62
R Precentral Gyrus	236	11,99	15	-25	77
L Postcentral Gyrus (BA5)	236	6,986	-6	-46	68
L ACC (BA32)	532	9,886	-3	17	35
L Medial Frontal Gyrus (BA6)	532	9,533	-12	5	53
L SMA (BA6)	532	7,835	-6	-4	71
R Precentral Gyrus	742	9,263	57	-7	29
R Superior Temporal Gyrus	742	8,998	54	8	-4
R Superior Temporal Gyrus	742	7,744	54	-13	2

Results of the contrast «L2 >baseline» (p<.001, no corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus	7303	18,058	24	-94	11
L Culmen	7303	17,037	-3	-64	-16
L Fusiform gyrus	7303	12.93	-39	-40	-16
R Superior Temporal Gyrus (BA22)	294	10,708	63	-7	-1
R Superior Temporal Gyrus (BA22)	294	7,628	63	-28	5
R Superior Temporal Gyrus (BA38)	294	6,285	54	11	-16
R MCC (BA32)	552	10,448	12	17	44
L SMA (BA6)	552	9,588	-12	5	53
R SMA (BA6)	552	8,361	12	-1	62
R Precentral Gyrus (BA 6)	387	9,818	48	-7	26
R Precentral Gyrus	387	7,908	57	-7	44
R Precuneus	387	6,227	30	-7	38
R IFG (p. Triangularis)	145	6.98	33	29	2
R Middle Frontal Gyrus	145	4,91	30	38	-4
R IFG (p. Orbitalis)	145	4,908	42	23	-10
R IFG (p. Opercularis)	101	7,986	42	14	17
R Middle Frontal Gyrus (BA9)	101	4.78	51	14	32

Results of the contrast «switch >baseline» (p<.001, no corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus	9832	20,809	24	-94	11
L Culmen	9832	14.97	-27	-58	-25
R Superior Temporal Gyrus	9832	13.80	60	-7	-1
R Postcentral Gyrus (BA3)	132	10,670	6	-34	65
R Insula Lobe	138	7,518	33	17	2
R IFG (p. Orbitalis)	138	6.72	39	29	-7

Annexe 5. Statistical tables of fMRI task results for late bilinguals.

Results of the contrast «L1 >baseline» (p<.001, no corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus(BA 18/19)	5368	13,982	24	-94	8
L Middle Occipital Gyrus(BA 18/19)	5368	13,103	-18	-94	5
R Precuneus (BA7)	5368	10.59	27	-73	38
R Precentral Gyrus (BA6)	645	12,013	42	-10	44
R Superior Temporal Gyrus	645	10,279	57	-37	5
R Superior Temporal Gyrus	645	8,712	63	-7	8
R Thalamus	119	8,572	24	-31	5
R SMA(BA6)	218	8,150	12	11	71
L SMA (BA6)	218	7,916	-6	8	56
R ACC (BA 32)	218	5,606	9	17	44

Results of the contrast «L2 >baseline» (p<.001, no corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus	4124	14,899	27	-91	8
R Fusiform Gyrus	4124	13,098	42	-52	-16
R Fusiform Gyrus	4124	11,752	27	-64	-10
L Insula Lobe	209	13,490	-36	8	2
L ACC	209	9,794	-15	29	-1
R Precentral Gyrus	550	12,143	42	-10	44
R Middle Temporal Gyrus (BA22)	550	9,224	60	-34	2
R Precentral Gyrus (BA6)	550	7,229	54	-10	26
R Globus Pallidus	130	11,744	21	-13	-1
R Thalamus	130	8,241	24	-31	14
L IFG (p. Opercularis)	619	11,603	-51	8	26
L Precentral Gyrus	619	9,885	-48	-10	38
L Postcentral Gyrus (BA43)	619	6,894	-60	-7	14
R SMA (BA6)	275	8,709	12	11	71
L SMA (BA6)	275	7,809	-6	8	56
L ACC (BA32)	275	5,608	-9	20	32

Results of the contrast «switch >baseline» (p<.001, no corr., k > 100)

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Fusiform Gyrus	4169	14,695	27	-64	-10
R Middle Occipital Gyrus	4169	14,061	27	-91	8
L Middle Occipital Gyrus	4169	12,372	-48	-67	-7
R Superior Temporal Gyrus	526	12,719	57	-37	5
R Precentral Gyrus	526	10,563	39	-10	41
R Precentral Gyrus	526	7,811	54	-10	26
L Precentral Gyrus	667	9,503	-48	-10	38
L IFG (p. Opercularis)	667	8,838	-51	8	26
L SMA (BA6)	229	8,128	-6	8	56
R SMA (BA6)	229	8,011	12	11	71

RESUME EN FRANÇAIS

Le langage est le moyen grâce auquel l'être humain a pu construire les sociétés que dans lesquelles nous habitons. Cette faculté propre à l'humain est fondamentale pour communiquer et exprimer nos idées et même si l'individu arrive à l'apprendre et à s'en servir de manière automatique et sans effort, il est tout de même un habilité très complexe. On estime que plus de la moitié de la population mondiale parle deux langues et que 40% de la population utilise ses deux langues quotidiennement (Grosjean, 2012). Ainsi, il semble fondamental d'étudier et de comprendre le phénomène de la cohabitation de plusieurs langues, que ce soit à l'échelle de la société ou celle du cerveau d'un individu.

Les psycholinguistes et les neuropsycholinguistes se sont assez rapidement intéressés à la manière dont deux langues cohabitent dans un seul cerveau. Ils se sont, donc, intéressés, par exemple, à la représentation de plusieurs langues dans le cerveau, à l'acquisition des langues premières et secondes, et aussi au phénomène de l'attrition. Depuis une quinzaine d'années, les chercheurs ont porté leur intérêt aussi sur le mécanisme qui permet aux bilingues de passer d'une langue à l'autre.

Les premières découvertes sur les aires cérébrales dédiées au langage remontent à il y a deux siècles et ils se basaient sur des examens post-mortem de cerveaux de patients ayant des troubles du langage. Grâce au développement des techniques de neuro-imagerie, les chercheurs ont pu commencer à étudier le cerveau on-line également sur des individus sains, ce qui a permis de vrais progrès scientifiques concernant la connaissance de cet organe.

Définir le locuteur bilingue n'est pas un travail facile à cause de l'hétérogénéité de celui-ci. Dans notre travail, nous nous sommes basés sur la définition donnée par Mohanty (1994) qui affirme que les personnes ou les communautés bilingues sont celle qui ont la capacité de mobiliser leurs compétences pour répondre aux exigences personnelles ou de la société dans une ou plusieurs langues afin de maintenir une bonne interaction avec un autre locuteur d'une ou de toutes ces langues. Ils peuvent rarement parler les deux langues à la manière d'un natif mais ils développent plutôt un comportement linguistique unique.

Wei (2000 : 6-7) identifie plusieurs types de locuteurs bilingues et certaines de ces définitions seront utilisées dans ce travail. Par exemple, le bilingue qui a appris deux langues pendant son enfance est appelé bilingue précoce. Il s'oppose au bilingue tardif lequel a appris une deuxième langue à l'âge adulte. Le bilingue simultané est celui qui apprend deux langues en même temps dès la naissance et le bilingue successif, celui qui apprend une deuxième langue alors qu'il a déjà partiellement acquis une première. Le bilingue équilibré, celui qui maîtrise de manière à peu près équivalente les deux langues et le bilingue dominant, celui qui connait et utilise davantage une langue par rapport à l'autre. Ces catégories se basent principalement sur deux concepts : l'âge d'acquisition (AoA) et la compétence dans une langue. On peut retenir que ce sont deux facteurs majeurs impliqués dans l'acquisition de la langue seconde (L2).

L'âge d'acquisition représente le moment auquel l'apprentissage d'une compétence ou d'un concept débute. Cela a un impact sur l'aboutissement de l'apprentissage de cette compétence. Quand on parle d'âge d'acquisition, on se réfère très souvent à la période sensible. Cette période est vue comme un créneau pendant lequel une expérience spécifique a un effet plus marqué sur le développement d'un comportement ou d'un habilité par rapport à la même expérience faite à un autre moment de la vie (Trainor, 2005). Dans le domaine de l'acquisition des langues, Lenneberg (1967) a proposé un âge critique pour l'acquisition des langues, avant la puberté, après lequel l'apprentissage se fera plus lentement et difficilement. En effet, pendant les premières années de vie, l'enfant apprend les concepts ou des habilités de manière implicite. Cet apprentissage se fait de manière automatique, inconsciente et sans effort alors que à l'âge adulte, l'individu apprend de manière plus explicite, consciente pouvant se traduire par plus de difficultés. Ainsi, l'acquisition d'une langue seconde sera différente selon l'âge auquel l'individu commence à l'apprendre : plus tard un individu commence à apprendre une langue, plus cela sera difficile amenant à une compétence inférieure dans certains aspects de la langue (Flege, Munro, & MacKay, 1995 ; Mackay & Flege, 2004).

La compétence d'une langue seconde est définie, selon Newport et al. (2002) comme le contrôle qu'un individu a sur le système sonore et la grammaire d'une langue et elle est évaluée en comparaison au niveau de compétence d'un monolingue de cette langue. Il nous semble important d'apporter quelques précisions sur ce point. En effet, il ne faut pas considérer la compétence et la dominance comme des synonymes. La

compétence est liée à des scores standardisés (Birdsong, 2014) alors que la dominance est une mesure relative basée sur la comparaison entre la performance d'une langue (par exemple la L1) et la performance d'une autre langue (par exemple la L2), sans prendre en compte le niveau de compétence dans les deux langues.

Les études menées sur des individus non pathologiques ont montré qu'il y a un fort lien entre l'âge d'acquisition et le niveau de compétence qu'un locuteur atteint. Les locuteurs qui ont été exposé pendant leur enfance à une langue, montrent un meilleur niveau de compétence par rapport à ceux qui ont été exposé plus tard (Newport, 2003). Cela dit, il n'est pas impossible pour un bilingue tardif d'atteindre un niveau de compétence équivalent à celui d'un natif.

Deux modèles ont essayé de décrire les effets de ses deux facteurs sur l'apprentissage d'une langue au niveau cérébral. Le premier modèle se base sur la distinction entre une acquisition implicite ou explicite d'une langue, le deuxième modèle donne plus d'importance à la compétence atteinte. Le modèle déclaratif/procédural de Ullman (2001) propose un modèle dans lequel le lexique mental fait partie intégrante de la mémoire déclarative, alors que les processus grammaticaux sont sous-tendus par la mémoire procédurale. Dans le cas où la langue seconde est apprise tardivement, les processus grammaticaux ne seraient plus sous-tendus par la mémoire procédurale mais plutôt par la mémoire déclarative. Ainsi, une activité neuronale plus importante dans les aires associées à la mémoire déclarative devrait être observée chez les apprenants d'une L2 par rapport aux locuteurs d'une L1 (Ullman, 2005). Le deuxième modèle est celui de l'hypothèse de convergence neuronale de Green (2003). Il propose une vision de la représentation de la L2 plutôt basée sur la compétence que sur l'âge d'acquisition. Il propose que les réseaux neuronaux qui sont déjà en place pour la L1 seront utilisés pour le traitement de la L2, et que plus la compétence dans la L2 va augmenter et plus les représentations de ces deux langues vont converger.

Les études de neuro-imagerie ont permis aux chercheurs d'identifier les aires cérébrales qui sont impliquées dans la production langagière. Dans une méta-analyse de plusieurs études, Indefrey et Levelt (2004) ont indiqué qu'il s'agit d'un réseau plutôt latéralisé à gauche qui comprend le gyrus frontal inférieur postérieur, les parties postérieur et moyenne du gyrus temporal supérieur et moyen, le gyrus fusiforme, l'insula antérieure, le thalamus et le cervelet. De plus, d'autres aires faisant partie du réseau impliqué dans le traitement de concepts résultent impliquées : le lobe pariétal inférieur

postérieur, le gyrus parahippocampal, le cortex préfrontal dorsomédial et ventromédial, et le cortex cingulaire postérieur.

Plusieurs études qui ont comparé une langue dominante versus une langue non dominante ont trouvé des différences au niveau des activations cérébrales. En effet, au début de l'apprentissage d'une L2, la production de la L2 est très contrôlée et les items de la langue dominante peuvent interférer avec celle-ci. La résolution de cette compétition est traduite au niveau cérébral par une participation plus importante des aires plus antérieures du cortex préfrontal qui sont impliquées dans le contrôle des langues. Donc, plus le locuteur devient compétent en L2 plus cette différence devrait disparaître. Cela dit, toutes les études ne montrent pas systématiquement ce pattern.

Une des premières études (Kim et al., 1997) à comparer bilingues précoces et bilingues tardifs montre une différence entre les deux populations dans l'activation corticale de la zone de Broca. Les auteurs ont trouvé une représentation différente de la L2 et de la L1 chez les bilingues tardifs alors que ce n'était pas le cas chez les bilingues précoces. Il a été cependant reproché à cette étude de ne pas avoir bien contrôlé la compétence langagière des participants et les différences trouvées peuvent être dues à une différence liée à la compétence. En effet, Chee et collègues (1999) dans une tâche de génération de mots n'ont pas retrouvé cette différence entre bilingues précoces et tardifs, avec deux groupes de participants évalués comme très compétents.

L'âge d'acquisition et la compétence langagière ont été également testés en lien avec la plasticité cérébrale. Tout au long de la vie d'un individu, le cerveau humain modifie sa propre structure. L'action d'apprendre, tout comme une lésion cérébrale vont entraîner une réorganisation du système nerveux. Ainsi, des études ont montré des modifications du cortex en termes de volume et densité de la matière grise ou blanche ou de l'épaisseur corticale (Marie & Golestani, 2016).

Une des premières études à avoir montré que les bilingues précoces ont une matière grise plus dense au niveau du cortex pariétal inférieur que les bilingues tardifs est celle de Mechelli et al. (2004). Les auteurs ont également remarqué que l'augmentation était liée à la compétence langagière. Une autre étude (Klein et al., 2014) a montré une épaisseur corticale plus importante au niveau du gyrus frontal inférieur droit chez les bilingues précoces par rapport aux bilingues tardifs et une corrélation positive entre l'âge d'acquisition et l'épaisseur corticale dans le gyrus frontal inférieur gauche.

Une des capacités les plus frappante des bilingues est leur capacité à parler dans une langue sans avoir des interférences dans l'autre et sans effort apparent. Cela est d'autant plus surprenant en sachent que les deux langues d'un bilingue sont toujours activées même quand il est en train de parler, lire, écouter dans une seule langue. Il a été suggéré que le niveau d'activation des langues puisse augmenter ou diminuer selon la modalité d'une conversation (Grosjean, 2006). Si le bilingue entretient une conversation avec un monolingue, sa langue A sera complétement activée alors que sa langue B sera très peu activée. Au contraire, si la conversation est faite entre des locuteurs bilingues parlant les mêmes langues, les deux langues seront également activées donnant lieu à des situations de langage mixte. Dans cette situation un processus de contrôle des langues permet la suppression des interférences. La sélection des langues (ou contrôle) se réfère au mécanisme cognitif qui contrôle quelle langue utiliser à un moment et contexte précis (Abutalebi et al. 2007).

Dans le domaine général, le control cognitif est défini comme un processus d'adaptation à une situation nouvelle ou complexe. Il permet de moduler les comportements automatiques dans des situations où l'action de routine ne serait pas la performance optimale. Cette capacité de flexibilité est impliquée dans plusieurs processus spécifiques de contrôle cognitif qui sont appelés les fonctions exécutives (FE). Elles incluent l'inhibition à une réponse non-pertinente, la planification, la sélection d'une action, le monitoring, la mise à jour, la flexibilité mentale, la détection d'erreurs et la correction de comportements (Ridderinkhof et al. 2011).

Au niveau cérébral, les processus exécutifs ont longtemps été liés aux régions préfrontales mis en évidence par l'étude de certains patients qui avaient une lésion dans cette zone et des comportements altérés en ce qui concerne la planification, l'inhibition et l'élaboration de stratégies. Des recherches plus récentes ont proposé l'implication d'un réseau plus large incluant aussi le cortex cingulaire antérieur, le cortex pariétal, les aires motrices et le cervelet (Collette & Salmon, 2014 ; Niendam et al., 2012).

Les études sur le contrôle des langues ont identifié plusieurs régions corticales et sous-corticales impliquées dans ce mécanisme : le cortex préfrontal (PFC), le cortex cingulaire antérieur (ACC), l'aire motrice supplémentaire (SMA), le lobule pariétal inférieur (IPL), le cervelet, le thalamus, le noyau caudé et le putamen (Abutalebi & Green, 2016).

L'aire la plus importante dans le contrôle des langues est le cortex préfrontal latéral. Il a été associé à la planification d'actions, l'inhibition, l'attention, la mémoire de travail et la sélection de réponses. Le lobule pariétal inférieur est impliqué dans l'évaluation de choix conflictuels, l'attention, la détection et le maintien d'une représentation parmi plusieurs réponses. L'aire cingulaire antérieure est impliquée dans la détection d'erreurs et dans la résolution de conflits et l'aire supplémentaire motrice dans l'initiation du discours et dans la résolution de conflits inter-langues. Les aires sous-corticales sont fortement impliquées dans le contrôle cognitif. Des lésions au niveau des noyaux gris de la base provoquent une production langagière pathologique. Le putamen, et le cervelet ont été associés à l'aspect moteur du contrôle du langage et le noyau caudé à la sélection des langues. Enfin, le thalamus est associé à la sélection du lexique et des représentations sémantiques.

Deux modèles proposent deux types de mécanismes permettant de contrôler les langues : le modèle du contrôle inhibitoire (Green, 1998) et modèle de la sélection spécifique à la langue (Costa & Caramazza, 1999). Le premier modèle affirme que la sélection de la langue est accomplie à travers un mécanisme inhibitoire qui empêche l'activation de la langue non cible. L'inhibition rend possible la sélection du mot cible dans la langue voulue et cette inhibition perdure au fil du temps. Cela implique que pour réactiver la langue inhibée, il faudra surmonter l'inhibition appliquée précédemment. Étant donné que l'inhibition utilisée pour contrôler une langue dépend du niveau d'activation de celle-ci, une forte inhibition sera nécessaire pour inhiber la langue dominante par rapport à la langue non-dominante et donc un effort plus important sera demandé au moment de la réactivation de celle-ci. Le deuxième modèle affirme qu'il n'y a pas de compétition entre les deux langues et que le mécanisme de contrôle tient compte seulement du lexique de la langue cible. Dans ce modèle, l'inhibition de la langue non-cible n'est pas nécessaire, mais c'est l'intention de vouloir utiliser une langue qui suffit à assurer l'activation des mots de la langue cible.

Les études qui se sont intéressées au contrôle des langues ont observé que le temps de réponse (TR) était plus long lorsque les sujets passaient d'une langue à une autre. Ce phénomène est appelé *switch cost*. Il est intéressant de noter que l'ampleur du *switch cost* dépend plutôt de la difficulté relative des deux tâches à accomplir durant l'expérience. Les *switch costs* ont tendance à être plus importants lors du passage à la tâche la plus facile que lors du passage à la tâche la plus difficile. Ce phénomène est expliqué par la

présence du processus d'inhibition actif comme suggéré dans le modèle de Green. Cependant, ce résultat n'a pas toujours été répliqué. Costa & Santesteban (2004) ont montré qu'un *switch cost* asymétrique n'est pas présent chez les bilingues très compétents lors du *switch* entre leurs deux langues dominantes mais aussi lors du *switch* entre une langue dominante et une langue non dominante. Les auteurs en ont déduit que lorsque les bilingues atteignent un très bon niveau de compétence dans deux langues, un mécanisme de sélection spécifique à la langue se met en place et l'inhibition, même d'une langue non maîtrisée, n'est plus nécessaire.

Les études en neuro-imagerie fonctionnelle ont confirmé l'importance du cortex préfrontal dorsolatéral, de l'ACC et de la SMA pendant le switching entre deux langues (Abutalebi et al., 2008; Hernandez et al., 2001; Hernandez, 2009; Wang et al., 2009) mais il n'existe à l'heure actuelle pas de consensus sur le rôle spécifique de ces aires. Des études supplémentaires sont également nécessaires pour identifier les circuits cérébraux utilisés lorsque l'on passe de la L1 à la L2 et inversement. En effet, les deux études (Abutalebi et al., 2007; Wang et al., 2007) qui se sont intéressés à ce phénomène ont trouvé des résultats divergents.

En ce qui concerne la plasticité cérébrale, deux études ont montré la modification d'aires impliquées dans le contrôle des langues. La première étude (Abutalebi et al., 2013) a montré une densité plus importante de matière grise dans le putamen de gauche chez des multilingues tardifs par rapport à des monolingues et la deuxième (Abutalebi et al., 2012) a montré que chez des bilingues précoces une densité plus importante au niveau de l'ACC était corrélée avec une meilleure performance dans la résolution de conflit suggérant un effet du bilinguisme précoce sur la modification de la structure cérébrale.

Depuis une quinzaine d'années, de nombreuses études ont montré des effets positifs du bilinguisme au niveau de la performance cognitive. En effet, étant donné que les deux langues d'un individu bilingue sont toujours activées, un besoin constant de contrôle cognitif est nécessaire pour éviter les interférences d'une langue sur l'autre ou pour choisir la bonne langue au bon moment. Cela a porté les chercheurs à penser que cet entrainement de contrôle constant pourrait amener à un avantage cognitif bilingue général et pas seulement limité au domaine du switching linguistique (Bialystok, 2009).

L’avantage bilingue a été étudié par le biais de tâches dans lesquelles l’individu doit ignorer les informations de distraction comme la tâche de Simon et la tâche Flanker (Eriksen & Eriksen, 1974). Hilchey et Klein (2011) ont proposé deux hypothèses sur l’avantage du control cognitif dérivé de l’effet d’entrainement. La première hypothèse est appelée l’avantage du contrôle inhibitoire bilingue (Bilingual Inhibitory Control Advantage hypothesis - BICA). Cette hypothèse repose sur l’idée que l’utilisation fréquente du mécanisme d’inhibition impliqué dans la sélection linguistique mène à une augmentation de son efficacité. Son renforcement amène à l’amélioration des performances aux tâches non linguistiques qui demandent une résolution de conflit. La seconde hypothèse avance un avantage bilingue global sur les performances cognitives et non limité seulement au traitement d’inhibition (Bilingual executive processing advantage - BEPA). En outre, les bilingues qui ont tendance à alterner entre deux langues quotidiennement ont montré une performance supérieure dans une tâche de changement non linguistique (Prior & Gollan, 2011; Soveri, Rodriguez-Fornells et Laine, 2011), confirmant un éventuel transfert des capacités langagières dans le domaine général.

Au niveau cérébral, il a été constaté que le bilinguisme précoce entraîne des changements dans la latéralisation et la localisation des processus cognitifs sous-tendant les compétences du contrôle cognitif. En effet, en comparaison aux bilingues, les monolingues ont montré une activation accrue dans l’IFG droit et les bilingues ont montré une plus grande activité dans l'IFG gauche.

En conclusion, les études qui comparent les groupes bilingues aux monolingues ont fourni de nombreux éléments allant dans le sens d'un avantage bilingue dans les capacités de contrôle cognitif non linguistique en raison de la gestion quotidienne de deux langues. Compte tenu de la forte variabilité au sein de la population bilingue, des études se sont focalisées sur certains facteurs caractérisant la population bilingue. L'hypothèse de l'effet du bilinguisme précoce postule qu'un avantage bilingue plus élevé devrait être présent chez les bilingues qui ont commencé à utiliser plus d'une langue au quotidien dès l’enfance. Plusieurs études (Carlson & Meltzoff, 2008; Poarch & van Hell, 2012; Luk, De Sa & Bialystok, 2011) ont corroboré cette hypothèse révélant des capacités supérieures de contrôle exécutif chez les bilingues précoces par rapport aux bilingues tardifs.

Toutefois, les études n'ont pas permis d'observer une preuve flagrante de l'avantage bilingue. La réplication de certains des effets indiquant un avantage cognitif chez les bilingues n'est pas toujours obtenue et elle semble limitée à des conditions expérimentales spécifiques

(Colzato et al., 2008; Costa et al., 2009). Par exemple, Paap & Greenberg (2013) ont conclu que le contrôle des langues typique des bilingues se rencontre également dans le discours monolingue. En fait, dans le contexte de communication, les monolingues doivent surveiller les signaux concernant la prise de parole, le changement de sujet, le changement de registre, le second degré, etc. Et même s'ils n'ont pas à faire face au problème de la suppression de la langue non cible, ils doivent constamment choisir parmi les candidats sémantiques et syntaxiques alternatifs. Enfin, même si les bilingues compétents ont des besoins supplémentaires de monitoring, de *switching* et de contrôle inhibiteur, ces exigences ne sont pas suffisamment importantes pour générer des différences de groupe dans le contrôle cognitif.

Dans un article récent, Paap, Johnson et Sawi (2015) ont affirmé que plus de 80% des études sur l'avantage bilingue réalisées après 2011 n'ont pas montré de différences entre monolingues et bilingues ce qui a soulevé la question de biais dans le système de publication des résultats et des pratiques de recherche douteuses. Rosenthal (1979) a signalé la tendance des chercheurs à soumettre uniquement des études qui montrent des résultats significatifs et à mettre de côté ceux avec des résultats non significatifs. De Bruin, Treccani & Della Sala (2015) indiquent 2 facteurs possibles : 1) les auteurs décident de ne pas publier des études avec des résultats nuls ou mixtes ; 2) les reviewers et les éditeurs sont enclins à plus rejeter les articles présentant des résultats nuls, négatifs ou mixtes que ceux signalant des effets positifs.

Hilchey, Saint-Aubin & Klein (2015) ont avancé le besoin d'un effort plus systématique et rigoureux pour contrôler les facteurs qui affectent les fonctions exécutives. Ils ont signalé une utilisation excessive de covariables susceptibles d'affecter les fonctions exécutives et suggèrent que cette pratique pourrait être à l'origine de l'avantage bilingue observé. Par exemple, Morton & Harper (2007) ont soulevé la question du statut socioéconomique (SES) montrant que l'avantage bilingue a tendance à disparaître lorsque les SES sont contrôlés.

Problématique générale.

1) Des facteurs tels que l'âge d'acquisition, la compétence, le type d'apprentissage sont connus pour influencer l'architecture du système des langues et le réseau de neurones impliqué dans le traitement langagier. Cependant, la plupart des études psycholinguistiques ont accordé peu d'attention à la variation entre les individus bilingues. Ce travail de thèse a comme premier objectif de mesurer attentivement

les compétences linguistiques des bilingues précoces simultanés et des bilingues tardifs successifs. Un éventail de tâches linguistiques, y compris un questionnaire sociolinguistique, a été utilisé pour évaluer la compétence langagière des deux langues de tous les sujets.

2) Il est généralement admis que l'acquisition d'une seconde langue (L2) a une influence sur la structure cérébrale utilisée pour le traitement du langage, mais l'impact de l'âge de l'acquisition de la L2 n'est toujours pas bien établi. L'objectif de ce travail est d'examiner les substrats neuronaux sous-jacents à la production langagière en comparant deux populations de bilingues. Nous allons étudier si l'activité neuronale chez les bilingues précoces simultanés, qui ont appris les deux langues à partir de la naissance, est différente de l'activité neuronale des bilingues tardifs, qui ont appris la deuxième langue plus tardivement dans leur vie, grâce à la technique de l'IRMf. En effet, en raison de la maturation cérébrale, les enfants et les adultes sont équipés d'une configuration neuronale et cognitive très différente ayant un impact important sur les compétences d'acquisition. Dans ce travail, nous avons étudié le réseau cérébral impliqué dans la dénomination d'images chez les bilingues précoces par rapport aux bilingues tardifs, afin d'établir l'influence de l'apprentissage simultané précoce de deux systèmes linguistiques par rapport à l'apprentissage tardif et successif.
3) L'utilisation de la langue et le contrôle cognitif sont profondément liés dans le traitement du langage bilingue. Afin de communiquer avec succès, les bilingues doivent choisir la langue correcte et éviter les interférences indésirables de la langue non utilisée. Cette situation conduit à une expérience de contrôle langagier tout au long de la vie. Chez les bilingues précoces, cette capacité est développée depuis la petite enfance et va être utilisée pendant l'âge adulte. Dans notre étude nous comparons des locuteurs qui utilisent les deux langues au quotidien, et qui ont une très bonne compétence dans les deux langues, mais qui diffèrent du point de vue de l'âge de l'exposition à la L2. Nous nous attendons à ce qu'une plus faible activation dans les zones impliquées dans l'inhibition, la sélection et le monitoring, c'est-à-dire la SMA, la DLPFC et l'ACC, devrait être présente chez les bilingues qui ont commencé à utiliser plus d'une langue au quotidien dès le début de leur vie, compte tenu de la nécessité de gérer deux langues lors du développement de leurs mécanismes de contrôle exécutif. Enfin, récemment il a été observé que le contrôle

des langues peut dépendre des capacités générales de contrôle cognitif (Linck, Schwieter et Sunderman, 2012). Afin d'étudier l'impact de l'âge d'acquisition sur les capacités de contrôle des langues, tous les participants ont non seulement été appariés pour la compétence linguistique, mais également pour leurs capacités de contrôle cognitif (flexibilité, inhibition) à travers de tests neuropsychologiques.

La présente étude tente d'évaluer l'effet de l'acquisition précoce de deux langues en termes de temps de réponse et de corrélats neuronaux de l'alternance linguistique comparant un groupe de bilingues simultanés précoces avec un groupe de bilingues tardifs successifs ayant une très bonne compétence dans les deux langues.

4) La comparaison de deux groupes qui diffèrent en termes d'âge d'acquisition de la L2 donne l'occasion d'explorer l'influence de la variation de l'expérience linguistique initiale sur les modifications de la structure du cerveau. Ces deux groupes varient selon la durée d'exposition à une langue seconde et à la manière d'acquérir cette langue. Les bilingues précoces simultanés utilisent deux langues depuis leur enfance, tandis que les bilingues tardifs ont commencé l'acquisition de la langue seconde à un âge plus avancé. Nous nous attendons à ce que l'apprentissage de deux langues au début de la vie puisse façonner la structure du cerveau en termes d'épaisseur corticale. Étant donné que le cerveau est affecté différemment aux variations de l'expérience sensorielle (Neville & Bavelier, 2002), nous pensons pouvoir trouver une signature du bilinguisme précoce dans la structure corticale. Ici, nous avons utilisé une mesure automatique et directe de l'épaisseur corticale à partir des images anatomiques pour détecter les différences chez les individus qui ont acquis deux langues simultanément au début de leur vie et des individus qui ont appris deux langues successivement.

Méthodologie

Tous les participants ont effectué plusieurs pré-tests se conformant aux critères d'inclusion qui étaient les suivants :

- Bilingues français-anglais ou anglais-français avec au moins un niveau C1 du Cadre Européen Commun de Référence pour les langues (CECR) dans les deux langues.
- Age > 18 ans

- Droitiers (Oldfield, 1971)
- Niveau d'études égal ou supérieur au baccalauréat.
- Bilingues précoces : âge d'acquisition des deux langues avant 3 ans.
- Bilingues tardifs : âge d'acquisition de la L2 après 10 ans.

Dans le cas des bilingues précoces, la L1 était la langue du pays où ils ont passé les premières années de leur vie.

Les critères d'exclusions étaient :

- contre-indication de l'IRM : claustrophobie, femmes enceintes ou allaitantes, addiction, lentille intraoculaire métallique, stimulateur cardiaque, corps étranger métallique, troubles neuropsychiatriques importants, clips chirurgicaux, refus d'être informé d'une anomalie détectée lors de l'IRM, antécédents d'épilepsie, personne sous protection juridique.
- score MMSE inférieur à 26
- Tout problème médical ou psychiatrique
- Age d'acquisition de l'une des langues entre 3 et 10 ans

Tous les participants ont pris la décision de participer à cette étude sans subir aucune pression. Comme recommandé par le comité d'éthique de la recherche (CPP13-025 / 2013-A01155-40), tous les participants ont fourni un consentement écrit formel pour participer à cette étude. Ils ont reçu la somme de 80 € pour leur participation.

Vingt bilingues français-anglais ont participé à l'expérience. 12 étaient des hommes et 8 étaient des femmes entre 20 et 40 ans (âge moyen des bilingues précoces = 24,7, SD = 3,3, âge moyen des bilingues tardifs = 28,7, SD = 6). La moitié d'entre eux étaient des bilingues précoces (groupe 1). Tous ont commencé à apprendre la L1 et la L2 dans leur petite enfance (avant l'âge de 3 ans). Le groupe 2 était formé par 10 bilingues tardifs parlant le français ou anglais comme L1 ou L2. Tous ont commencé à apprendre la L2 après l'âge de 10 ans (âge moyen = 11 ; SD = 1,2). Tous les sujets ayant un niveau élevé dans une troisième langue ont été exclus. Tous les bilingues précoces, à l'exception d'un seul, sont nés dans une famille dans laquelle chaque parent parlait l'une des deux langues. Tous les participants ont trouvé très important de maintenir un bon niveau de L1 et L2. Tous les sujets affirment utiliser les deux langues au quotidien ou au moins une fois par semaine.

Les participants ont réalisé une série de pré-tests linguistiques évaluant le niveau de compétence des langues et leur utilisation. Ces tests comprenaient un questionnaire

sociolinguistique (annexe n ° 1) évaluant l'âge auquel ils ont commencé à apprendre les langues, le type d'éducation (éducation bilingue ou immersion), la quantité d'input reçu dans les deux langues, leurs compétences linguistiques et la quantité d'exposition aux langues dans des domaines tels que la famille, les amis, les médias, les amis, la lecture et d'autres activités (p. ex. loisirs, sports, musique, etc.). Cette évaluation a permis de connaître l'âge d'acquisition de la L2 et d'avoir une approximation des compétences linguistiques (auto-évaluation) et de l'exposition globale à une langue donnée. Le niveau de compétence a également été évalué par le test Efficient Language Evaluation Online (test ELAO, http://elao.accentlang.com/fr/index.html), un test de fluence verbale (lexicale et catégorielle) et une tâche de dénomination d'images.

Les tests neuropsychologiques administrés comprenaient le MMSE (Folstein et al., 1975), le WAIS- empan auditivo verbal (Wechsler, 2000), TMT (Reitan, 1958) et Stroop Test (Stroop, 1935). Ces tests ont été administrés en français pour tous les participants.

Une tâche de dénomination d'images a été présentée aux participants lors d'une passation IRMf. Cette tâche consistait en trois conditions : deux conditions bloquées (dénomination en L1 ou L2) et une condition d'alternance linguistique. Le logiciel E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA) a été utilisé pour la présentation des stimuli. Pour s'assurer que la réponse correcte soit produite pendant l'expérience, les participants devaient nommer les stimuli ouvertement. Les réponses ont été enregistrées avec un microphone (FOMRI II) connecté à un ordinateur à l'extérieur de la salle du scanner. Pour l'expérience, nous avons utilisé un total de 168 dessins noir et blanc sélectionnés parmi le corpus de Snodgrass et Vanderwart (Snodgrass & Vanderwart, 1980) et du corpus du Center for Research in Language-International Picture Naming Project (Szekely et al., 2005). Chaque stimulus, 105 x 105 mm, a été présenté une fois pour les trois conditions, totalisant 504 stimuli pour chaque participant. Les images ont été choisies de telle sorte que les noms en français et en anglais n'aient pas de similitude phonologique («non cognats»). Les noms composés ont également été éliminés. Par exemple, l'image de "ball", qui est "balle" en français, et "butterfly", qui est un nom composé, ont été écartés. L'accord sur le nom à donner à l'objet (name agreement) moyen était de 91,1% pour le français et de 92,1% pour l'anglais. La familiarité moyenne de l'image (picture familiarity) pour le français était de 3,1 et pour l'anglais 3,4 sur une échelle de 1 à 5.

Le paradigme expérimental pendant la passation IRMf a consisté en 6 séries, d'environ 5 minutes chacune, où toutes les conditions ont été présentées de manière pseudo-aléatoire.

Les blocs d'activation étaient composés de 7 images. Pour tous les essais, chaque image a été présentée pendant 1500 ms, suivie d'une croix de fixation pendant 1000 ms. Chaque essai a débuté avec un signal visuel de 450ms pour un total de 2950 ms par essai. Un indice indiquant le mot "say" en anglais et le mot "dire" en français, signalait au participant la langue de réponse attendue. Dans la condition d'alternance, l'indice alternait sur chaque image d'une langue à l'autre. L'ordre des 6 séries, composé de 12 blocs d'activation, a été équilibré entre les sujets. Chaque bloc d'activation a été alterné avec une période de repos de 8850ms (2950x3ms), au cours de laquelle les sujets ont été invités à se reposer. L'expérience a été menée dans une session d'une durée d'environ 1 heure sur une IRM Philips ACHIEVA (3 Teslas) dotée d'une antenne tête SENSE à 8 canaux. La présentation visuelle a été assurée par un vidéoprojecteur Toshiba associé à un écran translucide. Les participants ont été équipés d'un casque audio MR CONFON et de bouchons d'oreille, permettant de les protéger du bruit de l'IRM. Une image anatomique 3D haute résolution de cerveau entier a été prise avant la tâche d'IRM fonctionnelle pour chaque participant. Elle était constitué de 170 images pondérées T1 (TR = 8,1 ms; TE = 3,7 ms; angle de bascule = 8 °; champ de vue (FOV) = 240 x 240 mm; taille de voxel = 1mm ^ 3). Les images fonctionnelles ont été acquises en utilisant une séquence EPI (Echo Planar Imaging) (TR = 2950 ms; TE = 30 ms; angle de bascule = 90 °; champ de vision (FOV) = 240x240 mm). Chaque volume était composé de 38 coupes axiales entrelacées de 3 mm d'épaisseur couvrant l'ensemble du cerveau (taille de voxel: 3 mm x 3 mm x 3 mm).

Pour chaque participant, nous disposions de 117 images fonctionnelles et une image anatomique T1 convertie du format DICOM au format NIFTI en utilisant le logiciel «MRIConvert» (Smith, 2011). Les images fMRI ont été traitées via le logiciel SPM12b (Statistical Parametric Mapping, Welcome Department of Imaging Neuroscience, Londres, Royaume-Uni, 2012, http://www.fil.ion.ucl.ac.uk/spm/), implémenté sous la suite MATLAB (R2015a , The MathWorks, Inc., Natick, MA, États-Unis).

Nous avons traité les données en utilisant un pipeline de prétraitement qui comprend un slice-timing, un réalignement, et une normalisation vers l'espace standard MNI permise via des paramètres calculés lors d'une étape de segmentation de l'image structurelle coregistrée sur l'image moyenne des images fonctionnelles, et enfin un lissage spatial via un noyau Gaussian de 6 mm de FWHM.

Au premier niveau, les images individuelles ont été analysées selon un modèle linéaire généralisé (Friston et al., 1994). Les six paramètres de mouvement de la tête du sujet calculés

lors de l'étape de réalignement ont été inclus dans le modèle en tant que régresseurs. Ces cartes statistiques étaient ensuite intégrées dans une analyse de groupe à effets aléatoires au second niveau nous permettant de calculer les contrastes d'intérêt. Trois effets principaux simples ont été testés : dénomination en L1 ; dénomination en L2 ; et dénomination en *switch*. Les contrastes de test de Student, en comparant les cartes statistiques entre trois conditions, ont été effectués en utilisant un seuil de $p < 0,05$ avec correction FWE (*Family Wise Error*), avec un seuil d'étendue de cluster de 100 voxels contigus. Lorsque aucune activation n'a été trouvée, nous avons utilisé un seuil statistique de $p < 0,001$, non corrigé pour des comparaisons multiples, avec un seuil d'étendue de 100 voxels contigus. La visualisation des activations et l'identification des structures anatomiques impliquées a été faite à l'aide de la toolbox xjView 8 pour SPM (Cui, Li, & Song, 2011). Les cartes statistiques de groupe étaient superposées sur un modèle 3D standardisé pour la visualisation en utilisant le logiciel MRIcron (Rorden & Brett, 2000).

Des analyses ultérieures ont été effectuées sur trois régions d'intérêt (ROI) : l'ACC gauche (x = -3, y = 14, z = 38), la SMA gauche (x = -3, y = 2, z = 59) et le DLPFC gauche (BA9 / 46, x = -45, y = 15, z = 25). Des ROI de sphères de 10 mm ont été générés via la toolbox Marsbar (http://marsbar.sourceforge.net). Nous avons étudié l'activité BOLD dans ces ROI durant la tâche de dénomination. Les paramètres des estimations du signal BOLD ont été exportés vers SPSS pour des analyses de niveau de groupe. Nous avons utilisé des *t-tests* pour identifier les effets de l'âge d'acquisition et nous les avons corrélés avec les résultats comportementaux.

Enfin, nous avons mesuré l'épaisseur corticale pour détecter les différences anatomiques entre les bilingues tardifs et les bilingues précoces. Une mesure automatique a été effectuée sur les images T1 via la toolbox Corthizon (Querbes, 2009). Une normalisation de l'épaisseur corticale a été effectuée pour tous les sujets en divisant le score de chaque région par l'épaisseur corticale du cerveau entier de chaque participant.

Les résultats.

Données comportementales : au niveau linguistique, aucune différence n'a été trouvée entre les deux groupes comme le montre le tableau suivant :

Tableaux 1. Caractéristiques des bilingues précoces et tardifs d'après leur âge, genre, AoA de la L2 et résultats des tests de langage.

	Bilingues précoces	Bilingues tardifs	p
Âge[3]	24.7±3.3	28.7±6.0	ns
Genre	3(f) / 7(m)	5(f)/5(m)	-
AoA de la L2	0**	11±1.2**	0.001
L1 français/anglais	6 (F)/ 4(E)	5(F)/4(E)	ns
L2 français/anglais	4(E)/ 6(F)	4(F)/5(E)	ns
Compétence en L1	5.4±0.5 / 88.9±5.8	5.7±0.4/92±3.1	ns
Compétence en L2	5.4±0.5 / 87±5.2	5.1±0.3 / 85±4.7	ns
Fluence verbale lexicale en L1	14.4±5.1	18.1±3.9	ns
Fluence catégorielle en L1	22.2±4.3	25.3±6.3	ns
Fluence verbale lexicale en L2	13.5±2.5	14.6±2.0	ns
Fluence catégorielle en L2	21.1±5.2	22.3±5.6	ns
Tâche de dénomination – L1	49.6±0.8	49.3±1.6	ns
Tâche de dénomination – L2	48.4±1.2	48.3±1.5	ns
Tâche de dénomination – switch	96.4±2.5	97.8±1.9	ns

Au niveau neuropsychologique, aucune différence n'a été trouvée entre les deux groupes comme le montre le tableau suivant :

Tableaux 2. Résultats des tâches neuropsichologiques chez les bilingues précoces et tardifs.

Tests neuropsychologiques	Bilingues précoces	Bilingues tardifs	p
MMSE	29.7±0.7	29.7±0.7	ns
Oldfield	92±9.2	94±8.4	ns
Stroop A	45.2±7.7	41.9±5.1	ns
Stroop B	51.9±6.6	49.2±6.3	ns
Stroop C	70.2±12.1	67±8.3	ns
TMT B-A	28.5±9.4	20.8±14.5	ns
TMT B-A/A	1.2±0.5	0.9±0.8	ns
WAIS endroit	9.7±2.3	9.2±1.9	ns
WAIS inverse	6.6±2.3	7.2±2.6	ns

Les réponses des participants ont été analysées pour identifier les différentes erreurs commises. Au total, 8,4% des essais ont été considérés comme des erreurs dont 6,3% étaient des omissions et substitutions, 1,7% des code-switching, et 0,4 des réponses disfluentes

[3] L'âge et l'âge d'acquisition sont exprimés en années. La compétence est notée sur la base des deux types de résultats ELAO : sur une échelle de 1 à 6 et en pourcentage.

(comme bégaiement). Les bilingues précoces ont réalisé 9,6% d'erreurs et les bilingues tardifs 6,9%.

Les erreurs. Nous avons effectué une ANOVA à mesure répétée avec "condition" (bloqué *vs switch*) et "langue" (L1 vs L2) comme facteurs intra-sujets et "Groupe" (bilingues précoces *vs* bilingues tardif) en tant que facteur inter-sujets. Un effet de langue a été trouvé. Les participants ont effectué plus d'erreurs pendant la dénomination en L2 (10,7%) que pendant la dénomination en L1 [7%, F (1,17) = 8,937, p = 0,008]. Un effet de condition a également été observé, les participants ont commis plus d'erreurs dans les essais *switch* (10,4%) que dans les essais en condition bloquée [7,3% ; F (1,17) = 13,353, p = 0,002]. Aucune différence entre les deux groupes n'a été trouvée [F (1,17) = 3,828, p = 0,07].

Les temps de réponse. Nous avons effectué une ANOVA à mesure répétée avec "condition" (bloqué *vs* switch) et "langue" (L1 vs L2) comme facteurs intra-sujets et "Groupe" (bilingues précoces *vs* bilingues tardifs) en tant que facteur inter-sujets. Seulement un effet de la condition a été trouvé. Les essais *switch* (1036ms) ont été plus longs que les essais bloqués [995ms; F (1,17) = 34.804, p = 000]. Aucun effet de groupe n'a été trouvé [F (1,17) = 0,062 p = 0,80].

Tableaux 3. Moyenne des temps de réaction des deux groupes pendant la tâche de dénomination d'images dans la condition bloquée et *switch*.

TRs	Bilingues précoces		Bilingues tardifs		Total	
	L1	L2	L1	L2	L1	L2
Bloquée	988 (05)	1000 (04)	994 (09)	996 (05)	991 (08)	998 (04)
Switch	1039 (06)	1021 (05)	1041 (08)	1042 (06)	1040 (07)	1031 (05)

Aucun effet d'interaction n'a été observé entre "condition" × "langue" [F (1,17) = 1,47, p = 0,24] indiquant un *switch cost* symétrique (L1 : 48 ms; L2 : 33 ms) ni entre "condition" × "langue" × "groupe" [F (1,17) = 1,30, p = 0,27] indiquant un *switch cost* symétrique pour les bilingues précoces (L1: 50 ms; L2: 21 ms) et les bilingues tardifs (L1: 46 ms; L2: 46 ms).

Nous avons corrélé le *switch cost* vers la L1 avec l'indice de dominance entre L1-L2 calculé en soustrayant la compétence en L2 à partir de la compétence en L1. Nous avons

trouvé une corrélation positive (r = 0,478, n = 19, p = 0,03), ce qui signifie que plus la L1 est dominante, plus l'effort pour passer de la L2 à la L1 est grand.

Données d'imagerie : Analyses globales de tous les participants : L1, L2, switch. Une analyse générale a été menée sur les trois conditions de dénomination (bilingues précoces et tardifs ensemble, n = 20) pour enquêter sur les zones cérébrales activées chez les bilingues très compétents. L'activation pendant la dénomination en L1 et en L2 par rapport à la ligne de base a révélé une activité bilatérale similaire dans les zones corticales des lobes frontaux et pariétaux, exception faite pour une activité neuronale latéralisée à gauche observée dans le gyrus frontal inférieur (zone de Broca, BA 44/45) et dans l'insula antérieure pendant la dénomination en L2. L'activité dans l'aire motrice supplémentaire (médial BA 6) a été plus étendue dans l'hémisphère gauche pour les deux conditions bloquées. Une activité bilatérale était présente dans le cortex visuel (BA 17, 18, 19), le gyrus fusiforme (BA 37), l'aire motrice supplémentaire (BA 6), le gyrus postcentral (BA 4), le lobule pariétal supérieur (BA 7), le cortex temporel supérieur (BA 21/22), le gyrus temporel postérieur inférieur (BA 20), le cortex cingulaire antérieur (BA 32) et le cervelet. L'activation du thalamus gauche n'a été observée que dans la dénomination L1.

La condition *switch* a révélé un pattern d'activation similaire par rapport à la ligne de base. A savoir, le gyrus précentral bilatéral (BA 6), le SMA et le cortex cingulaire antérieur (BA 32), le gyrus temporel supérieur (BA 22), le gyrus temporal inférieur postérieur (BA 20), le gyrus fusiforme (BA 37) et le lobe occipital (BA 17, 18, 19), le thalamus et le cervelet.

Une comparaison directe a été menée entre la condition de *switch* et la condition bloquée toujours sur la totalité des participants. Elle a révélé une activité accrue dans le lobule pariétal inférieur et supérieur bilatéral (BA 40/7), le gyrus précentral gauche (BA 6), le gyrus frontal moyen gauche et le cortex cingulaire moyen (BA 24 / 32).

La comparaison directe entre les bilingues précoces et les bilingues tardifs n'a révélé aucune différence d'activation.

Analyses en ROI. Nous avons extrait les estimations de paramètres du signal BOLD dans les trois régions d'intérêt : l'ACC gauche, la SMA gauche et le DLPFC gauche (BA9 / 46) pendant la condition *switch*. Aucune différence n'a été trouvée dans l'ACC gauche (Ts <1), SMA gauche (Ts <1), DLPFC (Ts <1). Une corrélation négative a été trouvée entre l'effet de *switch cost* et les estimations de paramètres du signal BOLD pendant la condition *switch*

du DLPFC (r = -0,669, n = 19, p = 0,002) et de la SMA (r = -0.658, n = 19, p = 0.002) mais pas pour l'ACC (r = -0.415, n = 19, p = 0.077).

Analyses de l'épaisseur corticale. Une mesure en région d'intérêt a été effectuée sur les images T1. Une série de *t-test* de Student a été effectuée sur les mesures de l'épaisseur corticale des bilingues précoces et des bilingues tardifs. Les contrastes ont montré des différences significatives dans deux zones de Brodmann. La zone 45 à droite (zone de Broca) était significativement plus épaisse chez les bilingues précoces (0,86 mm) que chez les bilingues tardifs [0,79 mm ; t(18) = -2,681, p = 0,015]. Le même pattern a été trouvé pour la zone 38 à gauche, la partie la plus antérieure du gyrus temporel supérieur (STG) et du gyrus temporel moyen, connu sous le nom de pôle temporel (bilingues précoces : 1,25 mm, bilingues tardifs de 1,15 mm ; t(18) = 2,103, p = 0,05).

Discussion

L'objectif de cette étude était d'élucider le rôle de l'âge d'acquisition dans deux populations de bilingues avec un niveau équivalent dans les deux langues et dans les capacités des fonctions exécutives. Tout d'abord, nous discuterons des résultats de l'évaluation des deux langues. Deuxièmement, nous discuterons des résultats fonctionnels des représentations des deux langues et les corrélats cérébraux impliqués dans le contrôle cognitif. Enfin, nous discuterons des changements structurels que l'apprentissage d'une langue depuis la petite enfance peut mener.

Dans ce travail, la volonté était de pouvoir comparer deux groupes qui diffèrent seulement par leur âge d'acquisition de la L2. La seule différence significative trouvée entre les deux groupes dans les tests d'évaluation linguistique a été observée dans le test d'auto-évaluation de la compétence écrite de la L2. Les bilingues précoces semblent être moins bons à l'écrit en L2 que les bilingues tardifs. Cela peut être expliqué par le fait que les bilingues précoces simultanés ont acquis les deux langues à la maison dans un contexte implicite et ont été scolarisés dans leur L1, tandis que les bilingues tardifs ont été exposés à leur première et deuxième langue dans un milieu scolaire.

En outre, nous avons constaté que l'indice de dominance L1-L2 était positivement corrélé avec le *switch cost* vers la L1. En d'autres termes, plus la différence est grande entre L1 et L2, plus l'effort demandé afin de passer de la L2 à la L1 est important. Ce résultat peut être interprété en termes d'un recours aux ressources d'inhibition différent dans la L1 et la L2.

En effet, Meuter et Allport (1999) affirment que la quantité d'inhibition appliquée à deux langues dépend de la dominance relative de ces deux langues. Un *switch cost* plus important sera présent lorsqu'on passe de la langue moins dominante à la langue plus dominante, car un effort majeur sera nécessaire pour réactiver la langue dominante qui avait été plus fortement inhibée au préalable.

L'un des objectifs principaux de cette étude était d'identifier les représentations cérébrales des langues chez des bilingues très compétents et d'apporter des éléments à la question de l'influence de l'âge d'acquisition chez les bilingues ayant atteint un haut niveau de compétence dans les deux langues.

Au niveau comportemental, nos résultats ont montré une différence significative en termes d'erreurs chez l'ensemble des participants précoces ou tardifs montrant un plus grand nombre d'erreurs faites lors de la dénomination en L2. On sait que lorsqu'un bilingue a l'intention de parler dans une langue, les représentations alternatives des deux langues sont activées (Costa et al., 1999; Hermans et al., 1998; Kroll, Bobb et Wodniecka, 2006) et, pour cette raison, un taux d'erreurs plus élevé est attendu, conjointement à des latences de réponse plus élevées, lorsqu'on utilise la langue moins dominante qui est donc la langue la moins bien maîtrisée. Cet effet a été interprété comme un effet d'exécution d'une tâche plus difficile en raison de la dominance d'une langue par rapport à l'autre (Misra et al., 2012). Cependant, dans notre étude, aucune différence n'a été trouvée en termes de temps de réponse et ce résultat est conforme aux activations fonctionnelles observées pour la dénomination en L1 et L2. En effet, des représentations neuronales similaires de la L1 et de la L2 ont été observées chez les bilingues précoces et les bilingue tardifs. Le réseau observé pour les deux groupes a déjà été identifié comme un réseau impliqué dans les tâches de dénomination d'images (Indefrey, 2011). Ces régions comprennent le gyrus frontal inférieur postérieur, les parties postérieures du gyrus temporel supérieur, l'aire motrice supplémentaire, le gyrus fusiforme et le cervelet.

Étant donné qu'aucune différence n'a été trouvée entre la dénomination en L1 et L2, nos résultats renforcent l'hypothèse selon laquelle les représentations de deux langues convergent lorsqu'un haut niveau de compétence est atteint dans les deux langues (Green, 2003b).

Il semble, en effet, que la compétence plutôt que l'âge d'acquisition exerce une influence plus importante sur les représentations des langues. Etant donné que la L2 se développe dans un contexte dans lequel le système L1 est déjà spécifié, il est plausible de penser que la L2 est traitée par le même réseau neuronal que celui de la L1. Ces résultats

suggèrent qu'une fois qu'une compétence est atteinte, la représentation neurale de la L2 converge avec celle de la L1 (Green, 2003; Perani & Abutalebi, 2005). Comme la production d'un élément lexical est plus pratiquée, la concurrence inter-langues peut être résolue plus automatiquement et elle exige moins d'effort cognitif, ce qui atténue l'activation des zones préfrontales liées au contrôle cognitif et à une représentation des langues similaire.

Le deuxième objectif de cette étude était d'étudier le rôle de l'âge d'acquisition chez les bilingues dans une condition *switch*. Les données comportementales ont montré une différence entre la dénomination bloquée et mixte. Dans le contexte mixte, les réponses étaient plus lentes et moins précises. Ces résultats sont conformes aux études antérieures qui ont montré un effet de contexte linguistique et suggèrent la présence d'un *switch cost* lors de l'alternance entre deux langues (Costa & Santesteban, 2004). Dans nos résultats, aucune différence comportementale n'a été trouvée entre les deux groupes et un *switch cost* symétrique a été observé suggérant non seulement que les bilingues précoces et tardifs peuvent atteindre le même niveau de compétence linguistique et de capacité dans le contrôle de la langue, mais aussi que les bilingues tardifs peuvent être vraiment équilibrés.

En résumé, notre étude ne montre aucun *switch cost* asymétrique, même chez les bilingues tardifs, ce qui nous permet d'affirmer que, même si une langue est apprise tard dans la vie, il est possible d'atteindre un niveau natif. Mais nous ne pouvons pas prouver l'existence du mécanisme spécifique à la langue, puisque nos participants n'étaient pas testés dans une troisième langue ou dans une tâche non-linguistique impliquant le contrôle cognitif.

D'un point de vue neurofonctionnel, la condition *switch*, par rapport à la condition bloquée, a révélé une activité accrue dans un réseau qui inclut le gyrus précentral gauche, le gyrus frontal moyen, le cortex cingulaire antérieur et le précuneus bilatéral et les lobules pariétaux inférieurs. Ce pattern d'activation a déjà été identifié comme des aires faisant partie d'un réseau impliqué dans le contrôle cognitif, et plus précisément dans le mécanisme d'inhibition (Wager et al., 2005).

Le cortex préfrontal gauche et l'ACC sont deux régions qui jouent un rôle prépondérant dans le contrôle cognitif. En particulier, l'activation du cortex préfrontal dorsolatéral a été rapportée dans des tâches dans lesquelles une sélection du stimulus cible est nécessaire pour surmonter une réponse non pertinente prépondérante (Heidlmayr, Doré-Mazars, Aparicio & Isel, 2016; Hernandez, 2009; Khateb et al., 2007; Wang et al., 2009). D'autre part, le cortex cingulaire antérieur est une région cruciale associée à la détection des erreurs et à la surveillance de conflits. Des études antérieures ont observé que ces deux

régions sont co-activées dans les tâches de conflit et ont un rôle crucial dans le choix des réponses alternatives, la commutation de tâches, le maintien d'une représentation nécessaire à la tâche actuelle et l'inhibition des éléments non pertinents détenus dans la mémoire de travail (Rodriguez-Fornells, De Diego Balaguer & Münte, 2006). Des études ont essayé de dissocier leurs rôles : l'ACC semble être responsable de l'évaluation de la demande de contrôle cognitif et de la transmission au cortex préfrontal d'un plus grand besoin de contrôle. Les lobules pariétaux inférieur et supérieur ont été liés à la sélection de la langue dans les études sur le contrôle de la langue (Abutalebi & Green, 2007; Hernandez, 2009) et aux fonctions exécutives distinctes comme l'inhibition, la flexibilité et la mémoire de travail (Niendam et al., 2012). L'activation du precuneus a été trouvée dans d'autres études d'alternance linguistique (Guo, Liu, Misra, & Kroll, 2011; Wang et al., 2007) et a été associée à l'inhibition de la réponse (Bunge et al., 2002), même si son rôle précis n'est pas totalement clair (De Bruin et al., 2014).

En outre, dans notre étude, une analyse ultérieure a montré qu'une activité plus importante dans le DLPFC et la SMA en contexte *switch* était corrélée avec un *switch cost* plus faible. Étant donné que la DLPFC et la SMA participent de manière cruciale au contrôle du langage et aux tâches de changement de langue (Abutalebi & Green, 2016), ces résultats suggèrent que les bilingues très compétents qui utilisent plus efficacement ces régions arrivent à mieux gérer les conflits. Une plus grande activité dans le PFC a déjà été associée à une meilleure performance chez les personnes ayant de bonnes capacités de contrôle (Bialystok, Craik, et al., 2005; Garbin et al., 2010).

En résumé, les résultats de cette expérience suggèrent que les locuteurs bilingues très compétents ne présentent pas de différences significatives selon qu'ils ont appris une langue tôt pendant l'enfance ou plus tard. En outre, ils ont montré un *switch cost* symétrique, ce qui suggère que la compétence atteinte plutôt que l'AoA affecte la façon dont les bilingues contrôlent leurs langues. Par ailleurs, le *switch* entre les langues chez les bilingues très compétents implique une activité cérébrale majeure dans des aires qui ont été déjà associées aux processus inhibiteurs, ce qui suggère que le changement de langue recrute un réseau de neurones engagé dans des fonctions de contrôle exécutif du domaine général plutôt qu'un réseau spécifiquement lié au changement linguistique. De plus, chez les bilingues très compétents, une activité plus élevée dans des aires impliquées dans le contrôle des langues, à savoir le DLPFC et la SMA, se traduit par une meilleure performance.

Dans cette étude, nous avons également étudié l'effet de l'âge d'acquisition d'une seconde langue sur la structure du cerveau. Nous avons pensé trouver une épaisseur corticale plus élevée chez les bilingues simultanés dans des aires typiquement impliquées dans le traitement du langage compte tenu de leur expérience de deux langues tout le long de leur vie. Nos résultats ont montré que les bilingues précoces simultanés ont un IFG plus épais que les bilingues tardifs. Ces résultats ont également été observés chez Klein et al. (2014) et fournissent des preuves que l'âge d'acquisition modèle la structure du cerveau. La différence dans le cortex frontal inférieur dans notre étude peut refléter une différence dans le processus d'apprentissage, c'est-à-dire un apprentissage implicite versus un apprentissage explicite. En effet, nos résultats sont compatibles avec les résultats de Hull et Vaid (2007) qui ont montré une implication de l'hémisphère droit dans le traitement des deux langues chez les bilingues précoces.

De plus, notre étude montre des effets de plasticité cérébrale associés à l'âge d'acquisition de la L2 dans le pôle temporel gauche : un cortex plus épais chez les bilingues précoces que chez les bilingues tardifs. Une épaisseur plus importante a déjà été observée dans cette région chez les bilingues par rapport aux monolingues dans l'étude d'Abutalebi et al. (2014). Elle a été associée au stockage des concepts lexicaux et à l'identification de ces concepts comme appartenant à une ou à l'autre langue afin de guider les processus de production et de compréhension de la parole (Abutalebi et al., 2014). Notre interprétation est que cette structure est une cible potentielle pour les changements au niveau cortical chez les bilingues précoces, car elle doit être recrutée pour guider la production de mots dans chaque langue de locuteur bilingue dès la naissance.

En conclusion, notre étude intègre le débat sur la relation entre la compétence langagière et la maturation neurale. La comparaison directe des bilingues précoces simultanés et les bilingues tardifs successifs est le moyen le plus approprié pour examiner les effets de l'apprentissage de deux langues. Cette étude n'a pas révélé un effet de l'âge d'acquisition sur la représentation des langues dans le cerveau et, de cette façon, elle clarifie le rôle de l'âge d'acquisition et celui de la compétence. Nous avons montré que les bilingues tardifs peuvent atteindre un niveau natif de compétence dans L2 et se comporter comme des bilingues précoces. Ces résultats consolident l'hypothèse de convergence (Green, Crinion & Price, 2006) qui propose qu'une fois qu'un bilingue atteint un haut niveau de compétence dans la seconde langue, la représentation de cette langue converge vers la représentation de la langue maternelle. Cependant, nous avons pu trouver une signature du bilinguisme précoce dans la

structure du cerveau qui confirme l'idée de changements cérébraux liés aux expériences, en particulier à l'expérience d'utilisation de plusieurs langues tout au long de la vie.

D'autres études doivent être réalisées afin d'étudier à quel point l'expérience d'une deuxième langue laisse ses marques sur la structure et le fonctionnement du cerveau. Récemment, les études sur le bilinguisme ont commencé à étudier la connectivité pendant le repos (*resting-state*) afin de déterminer les connexions fonctionnelles entre les zones cérébrales. Par exemple, Berken, Chai, Chen, Gracco et Klein (2016) ont trouvé une plus grande connectivité entre le gyrus frontal inférieur et les zones impliquées dans le contrôle cognitif, y compris le cortex préfrontal dorsolatéral, dans les bilingues qui ont appris le langage plus tôt dans la vie.

En ce qui concerne le contrôle des langues chez le bilingue, afin d'apporter une réponse claire sur le débat sur l'existence ou non d'un mécanisme de contrôle spécifique aux langues, il sera indispensable à l'avenir de comparer les performances des bilingues précoces et tardifs dans des tâches du *switch* linguistique et du *switch* non-linguistique.