

Neural aspects of second language representation and language control

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Abstract

A basic issue in the neurosciences of language is whether an L2 can be processed through the same neural mechanism underlying L1 acquisition and processing. In the present paper I review data from functional neuroimaging studies focusing on grammatical and lexico-semantic processing in bilinguals. The available evidence indicates that the L2 seems to be acquired through the same neural structures responsible for L1 acquisition. This fact is also observed for grammar acquisition in late L2 learners contrary to what one may expect from critical period accounts. However, neural differences for an L2 may be observed, in terms of more extended activity of the neural system mediating L1 processing. These differences may disappear once a more ‘native-like’ proficiency is established, reflecting a change in language processing mechanisms: from controlled processing for a weak L2 system (i.e., a less proficient L2) to more automatic processing.

The neuroimaging data reviewed in this paper also support the notion that language control is a crucial aspect specific to the bilingual language system. The activity of brain areas related to cognitive control during the processing of a ‘weak’ L2 may reflect competition and conflict between languages which may be resolved with the intervention of these areas.

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1. Introduction

Over the past two decades, a large body of neuroimaging studies has been devoted to the study of the neural organization of language (see for extensive reviews, [Démonet, Thierry, & Cardebat, 2005](#); [Indefrey & Levelt, 2004](#); [Price, 2000](#);). To date, the results of these brain imaging studies have not only converged with the findings derived from clinical aphasiology, but have also opened a number

of new perspectives to our understanding of the brain–language relationship. However, given the complexity and the limitations of the classical anatomico-clinical approach to the study of the neural basis of language, functional neuroimaging techniques represent an independent source of evidence. The value that functional neuroimaging adds to language research is to improve the perspective on the distributed anatomy of language. Thus, it can be used with considerable precision to identify the neural networks underlying the different domains of language processing. In general, functional neuroimaging studies have not only confirmed the anatomical knowledge gained from anatomico-clinical studies, but have indeed led to a number of new discoveries leading to substantial revisions of traditional concepts. Consider, for instance, Broca’s area: recent imaging evidence reports not only that the traditional Broca’s area located in the left inferior frontal gyrus can be functionally sub-divided into three regions,

Abbreviations: ERPs, event-related potentials; fMRI, functional magnetic resonance imaging; L1, first/native language; L2, second language; PET, positron emission tomography; ACC, anterior cingulate cortex; LIFG, left inferior frontal gyrus; STG, superior temporal gyrus; DLPFC, dorsolateral prefrontal cortex; VBM, voxel-based morphometry; Ba, Brodmann area.

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respectively, for phonology, semantics, and syntax (Bookheimer, 2002), but that it also plays a critical role in non-linguistic functions such as cognitive control (Koechlin & Jubault, 2006; Koechlin, Ody, & Kouneiher, 2003). Hence, hemodynamic studies offer a unique opportunity to properly assess the organization of language and cognitive functions in the human brain.

In the present article, an attempt will be made to illustrate the recent findings gained from functional neuroimaging concerning bilingualism. Research into the cerebral basis of bilingualism may be dated back to the early days of the anatomo-clinical approach. Following the well-known discoveries of Broca (1861), Scoresby-Jackson (1867) postulated that Broca's area is the language organ only for native languages, whereas the remaining part of the left inferior frontal gyrus might be responsible for second languages. Scoresby-Jackson gave this explanation to account for an aphasic patient who selectively lost the use of his second language after brain damage. The claim of differential localization for the L2 has dominated neuro-linguistics for over a century. Functional neuroimaging studies are now challenging this view and they may well further address questions raised in the psycholinguistic literature such as 'how the brain acquires a new language' and 'whether age of L2 acquisition or rather L2 proficiency is more important for, if any, cerebral differences?'

As a premise, it is first useful to remind that in the study of the bilingual brain, one should distinguish the network involved in the representation of language components such as word meaning and syntax from the circuits involved in the control of such networks (Green, 1986; Green, 1998, 2005). I will, therefore, first distinguish between language representations (Section 2), and the circuits involved in its control (Section 3), and then argue, contrary to some claims, that in a bilingual one or more languages are represented in the same network. However, as will be shown in the second part of the paper (Section 3), acquiring other languages alters the nature of the language network because it has to embed the later acquired language, a process that may involve competition and may be resolved with language control.

A comprehensive treatment of these issues is not possible in the space available. I will therefore mainly focus on hemodynamic studies such as fMRI and PET investigations (for a comprehensive and recently edited volume that covers a multitude of different research perspectives on representational and control issues the reader is referred to Gullberg and Indefrey (2006)).

2. The neural representation of L2

2.1. Acquisition and processing of L2 grammar

It is reasonable to suppose that the cognitive system mediating the meanings of words is common across languages (Francis, 1999; Kroll & Stewart, 1994). However, based on the assumption of a critical or sensitive period

for language acquisition (Birdsong, 2006; Clahsen & Felser, 2006; Hernandez & Li, 2007; Johnson & Newport, 1989; Lenneberg, 1967; Nowak, Komarova, & Niyogi, 2001), it is reasonable to argue that knowledge of the syntax of a language learned after such a critical period is represented rather differently from that of L1. As outlined by Paradis (1994), Paradis (2004), an L1 is generally acquired implicitly whereas an L2, if learned after such a critical period, is acquired explicitly in the sense that its grammar may be taught. More specifically, the processes involved in perceiving or in producing words and sentences may remain inaccessible to conscious awareness but individuals may still have declarative knowledge of the grammar in one case but not in the other. Conceivably, then, the grammatical aspects of an L2 may be represented differently (i.e., at a cognitive level). The Declarative/Procedural model (Ullman, 2001) provides a rationale for such a supposition. Its essence is that in normal monolinguals, words are represented in a declarative memory system whereas grammatical rules are represented in a cognitive system that mediates the use of procedures.

According to Ullman's Declarative/Procedural model (2001), Ullman's Declarative/Procedural model (2004), procedural and declarative knowledge are mediated by distinct neural systems involving a fronto-striatal network (i.e., Broca's area and the basal ganglia) for the first type and left temporal areas for the second. Indeed, the Declarative/Procedural model proposes that the fronto-striatal network mediates the use of grammatical rules (i.e., computes regular forms for production and decomposes such forms for comprehension) whereas the temporal memory system subserves the storage of irregular verbs. Past studies suggest that the fronto-striatal network is the main neural correlate of morpho-syntactical aspects of language processing (Caplan, Alpert, Waters, & Olivieri, 2000; Moro et al., 2001; Tettamanti et al., 2002) (but see Grodzinsky & Friederici, 2006 for a more comprehensive view on the neural structures mediating syntactical processing). Consider the implications of this view for L2 processing. Will Broca's area, along with the basal ganglia, be responsible only for L1 grammar processing or will it also underlie the processing of L2 grammar? Following Ullman (2001), Ullman (2004), L1 is acquired implicitly, mediated perhaps by an innate language learning mechanism only triggered during a critical period whereas an L2 is generally acquired explicitly via formal instruction and, hence, grammatical knowledge for L2 may not be processed through the neural structures related to implicit processing such as Broca's area and the basal ganglia, as is the case for L1 grammar.

An optimal testing ground for the declarative/procedural distinction has been the contrast in English between regular verbs to which '-ed' is added to form the past tense (e.g., talk-talked) and irregular verbs (e.g., come-came). Ullman (2001) argued that suppression of motor activity in Parkinson disease patients (a striatal dysfunction) correlates with greater difficulty in correctly producing the regular past tense, whereas excess motor activity in individuals with

symptoms of Huntington's disease (again a striatal dysfunction) is associated with overactive grammatical rule use.

Such data, however, may not be decisive as damage to the basal ganglia has an impact on cortical regions too (Hillis et al., 2002). Longworth et al. (2005) found no association between striatal dysfunction and selective impairment in the ability to form regular past tense in patients with Parkinson's disease and genetically-proven Huntington's disease. Likewise, Penke, Janssen, Indefrey, and Seitz (2005) showed in 10 German Parkinson's disease patients that basal ganglia circuits are not critically implied in German regular participle and noun plural inflection. Indeed, this evidence suggests that neocortical regions are critical for regular past tense processing. In healthy subjects, the processing of regular past tense verbs is linked to increased activity in the LIFG and in the left STG (Tyler et al., 2005). On this account, basal ganglia activation may be better interpreted in terms of the inhibition of competing alternatives (e.g., Crosson, 1985) and in suppressing alternatives in the process of integrating syntactic and semantic information (Friederici, Kotz, Werheid, Hein, & von Cramon, 2003), or to recruit controlled processes when language processing cannot rely primarily on automatic processes (Friederici, 2006).

To what extent is there functional neuroimaging evidence of the involvement of these brain structures in the acquisition of a second language? Following Ullman's hypothesis (2001), acquiring L2 grammar in adulthood does not rely on the same brain structures (i.e., the fronto-striatal network) that are used to process the native language. An alternative account hypothesizes that the acquisition of the L2 arises in the context of an already specified, or partially specified language system and the L2 will receive convergent neural representation within the representations of the language learned as the L1 (Green, 2003). Green's 'convergence hypothesis' (2003), claims that eventual neural differences between native and L2 speakers may disappear as proficiency increases.

One source of evidence in favor of the notion that the same structures underlie the acquisition of L1 and L2 comes from studies of artificial grammar learning. In a landmark study, Opitz and Friederici (2004) used fMRI to investigate the acquisition of language-like rules in an artificial language. Increased proficiency for the artificial language was associated with increased recruitment of Broca's area. In a further experiment, Friederici, Bahlmann, Helm, Schubotz, and Anwender (2006) showed that detecting violations in a sequence of syllables governed by a novel, and implicitly learned, phrase structure grammar differentially activated Broca's region in comparison to the detection of violations in a sequence of syllables governed by a novel, and implicitly learned, finite state grammar. The latter activated a region in the frontal operculum only. These results support the notion that the acquisition of an L2 (albeit an artificial one) is achieved through an existing network mediating syntax in L1.

More direct support can be gained by examining the activation exerted by different natural languages. In monol-

inguals, particularly relevant are studies of syntactic encoding for the characterization of the neural structures mediating grammar. Indefrey and colleagues (Indefrey, Hellwig, Herzog, Seitz, & Hagoort, 2004; Indefrey et al., 2001) used a scene description task and showed that sentence-level and local phrase level encoding activated regions caudally adjacent to Broca's area, underlining its importance in processing L1 syntax.

In bilinguals, the results of at least 12 functional neuroimaging studies have so far contradicted the predictions of the Declarative/Procedural model (Ullman, 2001, 2004). In fact, inspection of Table 1 shows clearly that overall both low and high proficiency bilinguals engage for L2 the same neural structures responsible for grammatical processing in L1 (for a review of ERPs studies focusing on L2 acquisition, see Osterhout, McLaughlin, Pitkanen, Frenck-Mestre, & Molinaro, 2006).

In studies investigating single word processing in L2 such as verb conjugation (Sakai, Miura, Narafu, & Murai-shi, 2004) and past tense word processing (Tatsuno & Sakai, 2005), increased activity around the areas mediating L1 syntax (i.e., Broca's area) was reported. Specifically, the study by Sakai et al. (2004) showed that the acquisition of grammatical competences in late bilingual twins is achieved through the same neural structures for processing L1 grammar. Twins were used as subjects to determine whether shared genetic factors influence their language abilities and neural substrates for Japanese (L1) and English (L2). For 2 months, the students participated in intensive training in English verbs (either regular or irregular verbs) as part of their standard classroom education. The authors suggested that 'the cortical plasticity for L2 acquisition led toward specialization of the left inferior frontal gyrus as in the case of L1, in spite of notable differences between L1 and L2 in the students' linguistic knowledge and in their performance in conjugating verbs' (cf. Sakai et al., 2004, p. 1233). These findings suggest a cortical mechanism underlying L2 grammar acquisition identical to that of L1. Similar conclusions were reached by Indefrey, Hellwig, Davidson, and Gullberg (2005) who investigated Chinese adults who had immigrated to the Netherlands where they learned Dutch as an L2 in classroom courses. Follow-up fMRI during a grammatical judgment task was employed after 3, 6, and 9 months of L2 teaching. Strikingly, the authors reported that as early as 6 months after the onset of L2 learning, the L2 recruited brain areas related to L1 syntax processing such as the LIFG. These findings were confirmed in a follow-up fMRI at 9 months post-onset. Two further fMRI studies in adults reported comparable evidence for shared brain structures underlying native language and the acquisition of L2 grammar (Musso et al., 2003; Tettamanti et al., 2002). In particular, Musso and colleagues (2003) highlighted Broca's area as a crucial structure in the acquisition of rules from a foreign language, but not for rules that are inconsistent with natural languages. Taken together, these functional neuroimaging findings suggest a cortical mechanism underlying L2

Table 1
Functional neuroimaging studies focusing on grammatical processing in L1 and L2 in bilinguals (see text for details)

Authors	Task and methods	Subjects	Age of L2 acquisition & L2 proficiency	Main findings
Luke et al. (2002)	fMRI during a syntax judgment task	7 Chinese (L1)–English (L2) bilinguals	Mean age of L2 acquisition = 12 years; High but not native-like L2 proficiency	Overlapping brain activity for L1 and L2 with peak activity in the left middle frontal gyrus
Wartenburger et al. (2003)	fMRI investigations during a grammatical judgment task	32 Italian–German bilinguals divided into three groups	Group 1: early and high proficient bilinguals Group 2: late but high proficient bilinguals Group 3: late and low proficient bilinguals	Independent of the level of L2 proficiency, more left prefrontal activity for late bilinguals when judging L2 sentences
Sakai et al. (2004)	fMRI during verb conjugation in L1 and L2	18 Japanese Twins learning English as L2 in high-school	Late L2 acquisition; Low proficiency	Increased brain activity around Broca's area for L2
Dodel et al. (2005)	Functional connectivity analysis based on an fMRI dataset on sentence production in L1 and L2	10 French (L1)–English (L2) bilinguals	Late L2 acquisition; Variable L2 proficiency ranking from low to moderate proficiency	Brain areas related to syntax production (LIFG, left basal ganglia, left precentral gyrus and SMA) functionally more linked during L2 sentence production than during L1
Indefrey et al. (2005)	Follow-up fMRI during a syntax judgment task at 3, 6, and 9 months after the onset of L2 learning	Native Chinese speakers in the initial state of L2 (Dutch) learning	Late L2 acquisition; Very low proficiency at the initial state and low to moderate L2 proficiency at the end-state	L2 recruitment of areas related to L1 syntax processing such as the LIFG after 6 months of learning
Rueschemeyer et al. (2005)	fMRI during grammatical judgment of sentences presented in the auditory modality	7 Russian–German bilinguals	Late L2 acquisition; High L2 proficiency	Specific engagement of the left inferior frontal gyrus, superior temporal gyrus and basal ganglia when processing the non-native language. More extensive STG activity for L1 than L2
Tatsuno and Sakai (2005)	Pre- and post-learning fMRI studies during past tense word processing	29 English learners from Japan divided into two groups on the basis of years of schooling in English	Late L2 acquisition Low L2 proficiency	Less activity within the left inferior frontal gyrus corresponding to a higher proficiency state (i.e., after the learning period)
Golestani et al. (2006)	fMRI during sentence production	12 French (L1)–English (L2) bilinguals	Late L2 acquisition Low L2 proficiency	More extended activation of the LIFG for L2 than L1
Rueschemeyer et al. (2006)	fMRI during grammatical judgment of the same sentences of Rueschemeyer et al. (2005) but presented in the visual modality	18 native speakers of German and 16 Russian (L1)–German (L2) bilinguals	Late L2 acquisition, High L2 proficiency	Only L1 engaged selectively more STG activity.
Hernandez et al. (2007)	fMRI during gender decisions on regular and irregular visually presented words in Spanish	12 Spanish–English bilinguals and 12 English–Spanish bilinguals	Early L2 acquisition for the Spanish–English bilingual group; Late L2 acquisition for the English–Spanish group; Proficiency matched for languages	Increased neural activity in the LIFG 44/45 for late L2 learners as compared to early learners
Jeong et al. (2007)	fMRI during an auditory comprehension task	30 native Korean speakers with two L2s: a morpho-syntactically close L2 (Japanese) and a morpho-syntactically distant L2 (English)	Late acquisition either for English than for Japanese; L2 proficiency was similar for the two L2s	Specific LIFG (pars triangularis) activation for L2 processing (either Japanese than English). Only the syntactically distant L2 activated selectively the pars opercularis of the LIFG and the superior frontal gyrus
Suh et al. (2007)	fMRI during reading of sentences with different levels of syntactic complexity	16 Korean (L1)–English (L2) bilinguals	Late L2 acquisition, Presumably high L2 proficiency as indicated by the TOEFL scoring	Overlapping activity in the LIFG for L1 and L2. Syntactic complexity related activity differences in the LIFG for L1 but not for L2

grammar acquisition identical to that of the L1, contrary to what the Declarative/Procedural model predicts.

A further relevant study is the fMRI investigation by Golestani et al. (2006) that required moderately fluent late bilinguals in French and English either to read, covertly, words in L1 or in L2 or to produce sentences from these words, again covertly, in either L1 or in L2. Overall, there was relatively greater activation in the left prefrontal cortex in L2 compared to L1 indicating increased effort and, consistent with increased working memory or sequencing/executive demands in L2 compared to L1, increased activation in the left inferior parietal region and in the right cerebellum. There was no systematic difference in the left prefrontal region activated in L1 as compared to L2 production and no shifts in the extent of activation with increased syntactical proficiency (measured outside the scanner). But interestingly Golestani et al. (2006) found that syntactical proficiency in English correlated with the distance in the peaks of activation for French and English. The distances between peak activation converged with an increase in proficiency. The authors suggested that such convergence might reflect the use of neural regions more tuned to syntax.

A further relevant finding of the Golestani et al.'s study (2006) was that increased proficiency in L2 was correlated with increased involvement of the basal ganglia. Golestani et al. (2006) consider such involvement as consistent with the use of basal ganglia for rule-based processing. However, such a finding is, again, not consistent with the direct application of the Declarative/Procedural model to the bilingual case because the model proposes that the basal ganglia are not involved in syntactic encoding in L2. As I have already pointed to data questioning the role of basal ganglia in rule-based processing, it is suggested that enhanced proficiency is associated with an increase in automaticity. In such circumstances, the basal ganglia may provide increased inhibitory control (see below).

2.2. The neural representation of L2 grammar: a matter of age of L2 acquisition?

In summary, the available evidence (see Table 1) shows that both low and high proficient late bilinguals engage for grammatical processing the same neural structures responsible for L1 processing (e.g., Rueschemeyer, Zysset, & Friederici, 2006; Suh et al., 2007). However, recent functional connectivity analysis (i.e., a statistical approach to measure the strength of connections between brain areas) on an fMRI dataset carried out during sentence production in low proficient bilinguals suggests that these brain regions may be differentially engaged by the two languages. The authors reported that the brain areas related to syntax production are functionally more linked during L2 sentence production than during L1 (Dodel et al., 2005).

As to the question of whether the neural substrate of L2 grammar processing is more dependent upon age of acquisition effects or rather proficiency effects, the available

evidence seems to point to the role of the former. In terms of extension and/or the peak activation, late L2 learners recruit more neural resources around the areas mediating L1 syntax (Golestani et al., 2006; Jeong et al., 2007; Rueschemeyer, Fiebach, Kempe, & Friederici, 2005; Sakai et al., 2004; Tatsuno & Sakai, 2005; Wartenburger et al., 2003).

It is worth mentioning that the only study investigating early bilinguals (Wartenburger et al., 2003) reported that the extension of the activity is identical for L1 and L2 while it is different when L2 is acquired after puberty. Similar results were reported by Luke, Liu, Wai, Wan, and Tan (2002) with subjects who learned L2 at the relative end-state of the critical period (for different definitions of the critical period see Singleton, 2005). The difference between early and late L2 learners was recently confirmed by an fMRI study that directly compared native and non-native speakers of the same language (Spanish) (Hernandez, Hofmann, & Kotz, 2007). Subjects were scanned while processing regular and irregular gender marked items in Spanish. Comparisons between groups revealed an increase in neural activity in the LIFG for late learners as compared to early learners. Taken together, these studies provide support for a 'critical period' for grammatical processing since late learners engage the prefrontal cortex more extensively. However, many of these studies were carried out with relatively low L2 proficiency subjects. It is therefore not clear whether the finding of more extensive activity along the left prefrontal cortex is due to age of acquisition or to factors related to the degree of L2 proficiency. The study of Wartenburger et al. (2003), on the other hand, shows that even when late bilinguals have a native-like L2 proficiency, they nonetheless activate the prefrontal cortex more extensively, suggesting that grammatical processing may be neurologically wired-in. Future studies employing different groups of late but very high proficiency bilinguals could further clarify whether the neural basis for grammatical processing depends on age of acquisition.

2.3. The lexical-semantic domain: a matter of L2 proficiency?

According to psycholinguists, during the early stages of L2 acquisition there may be a dependency on L1 to mediate access to meaning for L2 lexical items (Kroll & Stewart, 1994). This is hypothesized to occur because L2 words are generally acquired with reference to existing L1 concepts (i.e., L2 is mediated through L1 translation while L1 is concept-mediated). Increasing L2 proficiency reduces dependency on L1. Higher levels of proficiency in L2 produce lexical-semantic mental representations that more closely resemble those constructed in L1 and according to Green's 'convergence hypothesis' (2003), many of the qualitative differences between native and L2 speakers may disappear as proficiency increases.

It should be noted that the lexical-semantic domain has been relatively well studied by means of functional neuro-

imaging and comprehensive reviews are available in the literature (e.g., see Abutalebi & Green, 2007; Indefrey, 2006). Therefore, I will only summarize the main findings of these studies. In single word production paradigms such as picture naming, verbal fluency, word completion, and word repetition, neuroimaging studies have reported common activations in similar left frontal and temporoparietal brain areas that are engaged when monolinguals perform the same tasks, when L2 proficiency is comparable to L1 (Chee, Tan, & Thiel, 1999; Ding et al., 2003; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert 2000; Klein, Milner, Zatorre, Meyer, & Evans, 1995; Klein, Milner, Zatorre, Zhao, & Nikelski 1999; Klein, Watkins, Zatorre, & Milner, 2006; Klein, Zatorre, Milner, Meyer, & Evans, 1994; Perani et al., 2003; Pu et al., 2001). The activations found for L2 also overlapped with those underlying L1 lexical retrieval in the same bilinguals, underlining the fact that the same neural structures can be utilized to perform identical tasks for both languages. This happened irrespective of the differences in orthography, phonology and syntax among languages (Chee et al., 1999). In contrast, bilinguals with low proficiency in L2 engaged additional brain activity, mostly in prefrontal areas (Briellmann et al., 2004; Chee, Hon, Ling Lee, & Soon, 2001; De Bleser et al., 2003; Marian et al., 2007; Pillai et al., 2003; Vingerhoets et al., 2003; Yetkin, Yetkin, Haughton, & Cox, 1996).

Anatomical differences, mainly within the left prefrontal cortex, were also found for low proficient bilinguals in studies that used lexical decision and semantic judgment tasks in bilinguals (for example, lexical decision: Illes et al., 1999; Pillai et al., 2003; semantic judgment: Chee et al., 2001; semantic judgments: Rueschemeyer et al., 2005; Rueschemeyer et al., 2006; Wartenburger et al., 2003).

Finally, even if not strictly pertinent to lexico-semantic processing, proficiency related neuroanatomical differences were also reported in tasks such as story comprehension (Perani et al., 1998). Less proficient bilinguals, when compared to highly proficient bilinguals, activated less brain areas for sentence- and discourse-level processing in the left temporal lobe suggesting a less elaborated linguistic comprehension of the verbal material in L2. On the other hand, in a sentence production task, Kim, Relkin, Lee, and Hirsch (1997) observed a differential engagement of Broca's area for late L2 learners as compared to early bilinguals. However, since the authors did not provide background on the subjects' level of L2 proficiency, it is difficult to properly interpret these data.

Similarly to proficiency, language exposure may have strong influences on language inter-dependency in the bilingual lexico-semantic system. The effect of 'differential exposure' to L2 was investigated by Perani et al. (2003) in an fMRI study of two groups of early highly proficient bilinguals living in Barcelona (either Spanish-born and Catalan-born individuals). During L2 word generation,

Spaniards living in Barcelona (Catalonia) and hence mostly exposed to Catalan, as assessed by an extensive questionnaire, activated a reduced amount of left prefrontal cortex for word generation in L2 than Catalans, who were less exposed to Spanish (their L2). These exposure-related differences, observed in the left dorsolateral frontal cortex, are in line with evidence from previous studies in monolinguals, reporting that experience and practice on language task performance might result in decreased neural activity within the left prefrontal cortex (Thompson-Schill, D'Esposito, & Kan, 1999). As to the role of exposure, it is worth underlining that L2 can even replace L1 when bilinguals are no longer exposed to L1 (Pallier et al., 2003); behavioural and fMRI findings carried out in Korean adoptees suggested that L2 may replace L1.

In conclusion, the emerging picture for studies investigating the lexical-semantic domain is that, again, L2 is essentially processed through the same neural networks underlying L1 processing. L2 related differences are found for low proficiency and/or less exposed bilinguals in terms of greater engagement of the LIFG and/or selective engagement of prefrontal areas located outside the classical language areas such as BA 9, 46 and 47. It should be underlined that the age of L2 acquisition seems to have no major role in the lexico-semantic domain (Indefrey, 2006; Perani & Abutalebi, 2005). In other words and contrary to the grammatical domain, for lexico-semantic processing an L2 acquired late in life can be processed through the same brain areas processing L1. L2 proficiency thus seems to be the main determinant in the lexico-semantic domain since late bilinguals with native-like L2 proficiency activate the same identical areas for both languages (Perani & Abutalebi, 2005).

2.4. Why neural differences?

As a general conclusion, the studies reviewed above show that during lexical tasks, more left prefrontal activity may be necessary to support the processing of an L2 which is not mastered in a native-like fashion. For grammatical processing, proficiency seems not to be the crucial factor but rather the age of L2 acquisition. A late acquired L2 will rely upon additional activity in left prefrontal areas.

How can we interpret the finding of the greater engagement of the left prefrontal cortex when processing a second language? One possibility, in the case of grammar, is that the stronger involvement of the LIFG for L2 may be due to the fact that this brain region is already optimized for native language processing and will be, as a result, less efficient for a later learned L2. On the other hand, during lexical tasks, surrounding areas may be necessary to overcome the lack of sufficient proficiency for L2. Once sufficient proficiency is gained in L2, this extra activity in surrounding areas will disappear (Abutalebi & Green, 2007). In other terms, L2 related brain activity will converge to that of L1 (Green, 2003). Indefrey (2006) proposed two neuro-

physiological mechanisms to interpret the stronger L2 activation in the prefrontal cortex. First, bilinguals might compensate for lower efficiency by driving this region more strongly. The second mechanism proposed by Indefrey (2006) is based upon the principles of ‘the efficiency of neural organization’, i.e., the number of neurons necessary to perform a given task. In the latter case, performance can be negatively correlated with either the extent or the peak of activation. As argued by Indefrey (2006), studies reporting negative longitudinal changes (i.e., a decrease of brain activity) in the LIFG following a learning period (Sakai et al., 2004; Tatsuno & Sakai, 2005) may support the notion of the efficiency of neural organization.

An alternative possibility, and not necessarily in contradiction to the mechanisms proposed by Indefrey (2006), is that the activity within the prefrontal cortex may reflect executive control over access to short- or long-term memory representations (Fletcher, Shallice, & Dolan, 1998; Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997) such as grammatical or lexical representations to assist L2 processing. On this account, a relatively ‘weak’ L2 system (for instance, a low proficient L2) may be processed through neural pathways related to ‘controlled processing’ such as brain structures related to cognitive control while a ‘strong’ L2 system (i.e., a high proficient L2) is processed in a more native-like fashion and, hence, in a more automatic manner. This hypothesis will be discussed in detail in the next section.

3. Language control

3.1. An Interpretation of the prefrontal effect

Especially in the case of word production studies in the lexical-semantic domain, but also for grammatical tasks as reviewed above, differential activity found for a low proficient L2 is located (i) in the same L1-related prefrontal networks but engaged to a greater extent for L2 and/or (ii) in areas more anterior to the classical language areas such as in BA 9, 46, 47 that are related to cognitive control (Miller & Cohen, 2001). Once comparable proficiency to L1 is achieved for L2, these prefrontal activations disappear, strongly supporting the neural convergence hypothesis (see Green, 2003; Perani & Abutalebi, 2005). Note that the idea that the neural representation of an L2 converges with that of an L1 does not deny that in certain cases, the reverse will apply. For instance, when individuals learn to read in L2 first, the substrate for reading L1 will converge with that of L2 (see Abutalebi et al., 2007).

Functionally, establishing evidence of neural convergence requires that we consider the effects of proficiency upon L2 processing especially in the context of language control. But to what exactly does the notion of language control refer? Language control in the field of bilingualism may be best exemplified in the domain of lexical processing because of the multitude of available psycholinguistic studies (see for

review: Costa, 2005; Costa, Santesteban, & Ivanova, 2006).¹ Consider, for instance, the case of an English–French bilingual who has to retrieve the name ‘chat’ (cat) during a picture naming task in L2 (French). Will the word ‘chat’ compete only with other L2 semantically related items, such as ‘chien’ (dog), and ‘souris’ (mouse), as well as with phonologically similar ones like ‘chou’ (cabbage), or rather will the word ‘chat’ also compete with L1 translation equivalents such as ‘cat’, and semantically related items such as ‘dog’? Language control in bilinguals refers to the notion that there will be competition between lemmas in L1 and L2 (De Bot, 1992; Green, 1986; Green, 1998), which will in general be solved by inhibiting any active, non-target language (Green, 1998). This inhibition, and as a result, the need to ‘control’ L2 output, is especially prominent when an L2 is mastered with a low proficiency (Abutalebi & Green, 2007). Indeed, the frequent occurrence of L1 interference during the use of a weaker L2 (Grosjean, 1992) demonstrates that bilinguals need to ‘inhibit’ L1 for successful L2 output. At low levels of L2 proficiency, individuals will struggle to produce the correct name for a picture or to name a word, and such difficulty may have a number of sources. The neural connections between the concept, lemma and word form may be weaker. Lexical retrieval takes more time for a low proficient L2 (Snodgrass, 1993; Kroll & Stewart, 1994). Such differences in relative strength offer one reason to expect a difference in prefrontal activation and a change with proficiency. A second potential source of difficulty is interference from a prepotent concept name. The low proficient L2 speaker must inhibit unwanted L1 lexical items during L2 word production. On this view, any ‘prefrontal effect’ will also reflect between language competition involving controlled rather than automatic processing of L2. Certainly, once a speaker achieves higher levels of proficiency in L2, overt intrusions (Poulish & Bongaerts, 1994) become infrequent. A decrease in interference is to be expected to the extent that the system underlying the use of L2 is differentiated from that of L1 (see for a recent discussion Hernandez, Li, & MacWhinney, 2005). Third, the actual process of generating a lexical item will be more practiced and so demand less effort. We may expect then that with growing proficiency, the bilingual speaker may be less in need of controlled processing in normal language use except in the context of recent use of the L1 or in circumstances involving overt language switching. Competition can be resolved more automatically or the resolution of lexical competition may become internal to the lexico-semantic system.

¹ Note that this does not deny the importance of competition and controlled L2 processing during grammatical or phonological tasks (e.g., Segalowitz & Hulstijn, 2005). In fact, some psycholinguistic studies specifically emphasize controlled processing in the domain of grammar processing (see, for example, Doepke (1998) for grammatical competition during language acquisition in early bilinguals and Bordag (2004) for gender competition during grammatical encoding) and in the domain of phonology (i.e., Jared & Kroll, 2001; Jared & Szucs, 2002; Roelofs & Verhoef, 2006).

At the neural level, reduced dependence on control mechanisms is indexed by a decrease in prefrontal activity. Expressed differently, we should expect that the patterns of activation will differ substantially from native speakers at low levels of proficiency. The implication is that it would be false to infer that L2 is differentially represented (at the neural level) from L1 on the basis of neuroimaging data. Why should an L2 that is mastered with a low degree of proficiency be represented more extensively at the brain level (in terms of more brain areas, i.e., the prefrontal effect)? Consider that a less proficient L2 speaker knows only, for example, 1000 words as compared to the 10,000 or so words for her/his native language. It may seem paradoxical that these 1000 words are represented in larger brain areas. As a consequence, the prefrontal effect cannot be a question of language specific neural representations (L2 lexical items differentially represented from L1 lexical items), but necessarily an issue of processing-specific demands: the cognitive effort to process a weak system is higher than to process a strong system.

There is also a good analogy to the monolingual case: consider a situation in which you have to choose between lexical alternatives during a verbal task. If individuals are well trained in the task (i.e., after multiple task-specific training sessions as compared to a non-trained session), functional neuroimaging reveals reduced involvement of left prefrontal structures (Brodmann areas, 9, 46, 47; see Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999). It is unlikely that the neural representation of lexical items has changed in these monolinguals. Indeed, the interpretation put forward to explain these plastic changes was that cognitive effort is reduced for a well-mastered task and this results in less prefrontal activity (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999). Hence, the deactivation of the left prefrontal cortex may be linked to the decrease of processing demands inherent to the task rather than any change in neural representation of lexical items in that region. Retrieval, correct selection and maintenance of lexical items will become more tuned and more automatic because subjects are familiar with the task. Specific to the bilingual case, the left prefrontal effect may also index competition that is occurring between a weak L2 and a prepotent L1 that may be resolved with inhibitory control (Abutalebi & Green, 2007). In line with this assumption, Rodriguez-Fornells, De Diego Balaguer, and Münte (2006) have proposed that two interrelated control/inhibitory mechanisms might regulate competition in bilinguals: (a) a top-down control inhibitory mechanism could be implemented by the prefrontal cortex when language schemas are activated and (b) this prefrontal selection/inhibition mechanism could interact with a more local and bottom-up inhibitory mechanism that regulates the level of activation of the non-target language during competition. Both Rodriguez-Fornells et al. (2006) and Abutalebi and Green (2007) argue for the central role of the prefrontal cortex for language processing

in bilinguals because of its strategic position and interconnectivity with a multitude of neocortical and subcortical areas (see for a review Miller & Cohen, 2001). Following Petrides' two-stage hierarchical subdivision, the prefrontal cortex may be sub-divided into two distinct regions (Petrides, 1998). The dorsolateral prefrontal cortex (Ba 9 and 46) would carry out sequential processing and self-monitoring functions, whereas the ventrolateral prefrontal areas 45 and 47 are engaged in a lower level function entailing comparison between stimuli in short-term memory as well as the active organization of responses sequences based on conscious explicit retrieval of information from posterior cortical association systems (Petrides, 1998). The two-level hypothesis makes a clear distinction between active-controlled (strategic) retrieval, which requires the engagement of the inferior prefrontal cortex, and automatic retrieval that does not (Petrides, 1998). Active retrieval implies conscious effort to retrieve specific information (i.e., a word to be generated or a rule to be respected) guided by the subject's intention and plans. This attempt at retrieval may be self-generated or set up by the instructions given to the subject. As outlined above, in the bilingual case, the distinction between active-controlled vs. automatic retrieval may have strong implications. Producing words, producing sounds, or respecting rules in a weak L2 may be a 'non-automatic' task, while processing in an L1 may be 'automatic' and hence only for the former the engagement of the inferior prefrontal cortex could be necessary because L2 is processed in a controlled manner. In the following section, I will illustrate that controlled processing (i.e., language control) is not achieved solely through the intervention of the prefrontal cortex but, like many other cognitive functions, through a dedicated network of brain areas.

3.2. *The neural basis of language control in bilinguals*

Using various language paradigms, functional neuroimaging studies carried out with bilinguals have recently attempted to characterize the neural basis of language control processes. I will consider paradigms such as language switching, language translation and language selection in the face of prepotent interferences from a prepotent language. These paradigms may be very informative since language switching, language translation and selection have in common an important cognitive load: a current task must be inhibited (i.e., speaking in language A) in favor of the new task (speaking in language B) in the case of switching and translating and withholding a potential prepotent response (i.e., from a non-target dominant language) when selecting items of a weaker language in the case of language selection. Therefore, these tasks may heavily rely upon cognitive control mechanisms.

A PET study on bilinguals performing translation and switching tasks based on visually presented words showed that switching between languages increased activation in Broca's area and the supramarginal gyrus (Price, Green, & von Studnitz, 1999). On the other hand, word translation

increased activation in the ACC and basal ganglia structures (Price et al., 1999). The involvement of subcortical structures along with activity in the left prefrontal cortex was also reported by the fMRI study of Lehtonen et al. (2005) during sentence translation in a group of Finnish–Norwegian bilinguals. Language switching in picture naming (compared to non-switching trials) increased fMRI responses in the left dorsolateral prefrontal cortex (Hernandez et al., 2000; Hernandez et al., 2001; Wang, Xue, Chen, Xue, & Dong, 2007) and when switching into the less proficient language the prefrontal activity was paralleled by activity in the ACC (Wang et al., 2007).

Two other fMRI studies showed that, when controlling interference from the non-target language during tacit naming (Rodriguez-Fornells et al., 2005) and during reading (Rodriguez-Fornells, Rotte, Heinze, Noesselt, & Munte, 2002) in the target language, bilinguals activated the left dorsolateral prefrontal cortex. In the former experiment, Rodriguez-Fornells et al. (2005) used a go/no-go covert naming task in a highly mixed bilingual context and showed that, in order to control the interference from the non-target language, the subjects activated the left middle prefrontal cortex (BA 9/46) and the SMA. Similar findings were found by employing the adaptation paradigm (see Chee, 2006). In adaptation paradigms, similar stimuli such as words belonging to the same language are contrasted to stimuli belonging to two different languages. For instances, Chee, Soon, and Lee (2003) studied word repetition within and across languages and only the ‘across language’ condition entailed more extended left prefrontal activity (see also Klein et al., 2006, for similar findings). In a further adaptation paradigm, Crinion et al. (2006) reported that left caudate activity was sensitive to changes in the language but not to a within language condition.

In line with these findings, Abutalebi, Annoni, et al. (2007) have shown that the specific activity of the left caudate in bilinguals depends on the language and task context. Naming in L1 in a bilingual context increased activation in the left caudate and ACC; this activity was absent when subjects were placed in a monolingual L1 naming context. The influence of the situational context was also shown by means of ERPs investigations (Elston-Guettler, Gunter, & Kotz, 2005; Elston-Guettler, Paulmann, et al., 2005) emphasizing that language control may be specific to bilingual language processing insofar as it occurs whenever bilinguals are faced with handling two language systems but may be absent when faced only with a single language. Interestingly, in the Elston-Guettler et al. (2005) study, bilinguals had to view a movie either in L1 or in L2 before a semantic priming task. For subjects who viewed the movie in L1 but performed the priming task in L2 there was a significant L1 interference effect upon L2 processing (i.e., as evidenced by RTs and modulations in the N200 and N400 components of the ERPs). On the other hand, these interferences were absent in bilinguals who viewed the movie in L2 before performing the priming

task in L2 (for similar findings see Paulmann, Elston-Guettler, Gunter, & Kotz, 2006).

Finally, it is worth noting that the above mentioned hemodynamic studies investigated only language production, and with the exception of the study of Lehtonen et al. (2005), production was investigated only at the single word level. It is therefore remarkable that in a recent study focusing on the auditory perception of language switches during comprehension of narratives (Abutalebi, Brambati, et al., 2007) a neural network consisting of the ACC and the left caudate was reported when subjects perceived a switch into the weaker language (i.e., the less exposed language). In general, language comprehension is thought to be a more passive and automatic task than language production (Abutalebi, Cappa, & Perani, 2001). The fact that a cognitive control network is engaged even during auditory perception of a switch, strongly emphasizes the fact that the bilingual brain may be equipped with a dedicated cognitive mechanism responsible for the correct selection of the intended language. This view finds strong support in the study of bilingual aphasia. Case reports have shown that lesions to a left prefrontal-basal ganglia circuit not only cause involuntarily switching between languages, but may also cause interferences from the non-target language during naming tasks (e.g., Abutalebi, Miozzo, & Cappa, 2000; Mariën, Abutalebi, Engelborghs, & De Deyn, 2005).

Although the results of the neuroimaging studies may depend, at least partially, on the paradigms used, the emerging picture points to the involvement in language control involving a set of brain areas, i.e., the caudate nucleus, the prefrontal cortex, the ACC and the supramarginal gyrus (see Fig. 1 for a summary of findings). These structures are classically related to cognitive control (Abutalebi & Green, 2007; Braver & Barch, 2006; Dosenbach et al., 2006).

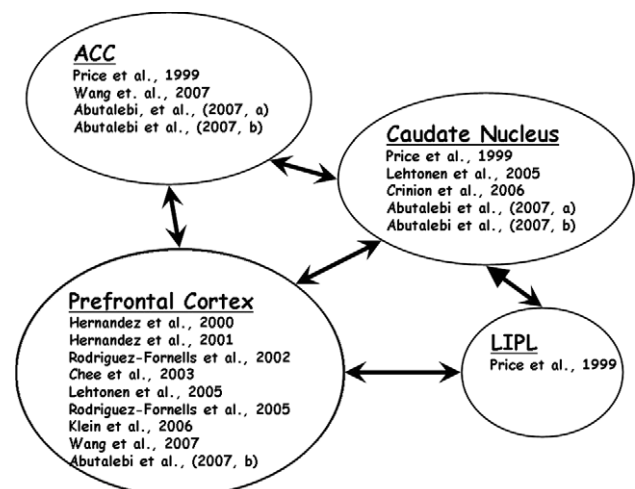


Fig. 1. Summary of the findings of functional neuroimaging studies investigation tasks such as switching between languages, translation and language selection. As evidenced by the figure, these tasks engage various components of the cognitive control network (see for details of the cognitive control network, Abutalebi & Green, 2007).

Crucial for the development of future neurocognitive models of bilingual language processing, the available neural evidence on language control in bilinguals shows that multiple neural levels of control are involved (prefrontal – ACC – subcortical and parietal) and so cognitive accounts that focus on a single level of control (e.g., competition between lemmas or competition between goals) may be insufficient to explain lexical retrieval in bilinguals (for discussion of this issue see [Abutalebi & Green, 2007](#)). Cognitive models of language selection will also need to characterize the neural resources required ([Green, 1986](#); [Green, 1998](#); [Green & Price, 2001](#)). As to the effects of proficiency upon the cognitive control mechanism, there are good indications that cognitive control networks are specifically engaged when it comes to the task of processing a low proficient L2. For instance, the studies that disentangled the single switching trials in order to observe whether it is more difficult to switch into L1 or into L2 have so far shown that prefrontal along with ACC and caudate activity is even more necessary when switching into a less proficient L2 ([Abutalebi, Annoni et al., 2007](#); [Wang et al., 2007](#)). These proficiency related differences have also reported in ERPs studies ([Alvarez, Holcomb, & Grainger, 2003](#); [Elston-Guettler et al., 2005](#); [Jackson, Swainson, Cunningham, & Jackson, 2001](#); [Proverbio, Leoni, & Zani, 2004](#)).

A question remains as to whether the cognitive mechanism that allows the selection of one language among others relies on a language-specific neural module or general executive regions that also allows switching between various competing behavioural responses including the switching from one linguistic register to another ([Chee, 2006](#)). Behavioural evidence indicates that the process of selecting one language improves skills in selective attention (e.g., [Craik & Bialystok, 2006](#)) and that bilinguals show less interference in a version of the Simon task ([Costa, Hernandez, & Sebastian-Gallés, 2008](#)) suggesting that bilingualism in general has positive repercussions for general executive and cognitive control functions.

4. Conclusions

The evidence reviewed in this paper supports a dynamic view of the neural basis of L2 processing. First, concerning language acquisition, L2 seems to be acquired through the same neural structures responsible for L1 acquisition. This appears to be the case for the acquisition of grammar in late L2 learners contrary to what one may expect because of the notion of critical periods. However, as reviewed earlier, neural differences between L1 and L2 may exist, for both grammatical processing and lexico-semantic processing. These differences are particularly prominent for a weak L2 system, that is, in the initial stages of L2 acquisition and/or when L2 is processed with a non-native-like proficiency. As to the anatomical location of these differences, two kinds of neural differences between L1 and L2 were

observed: first, increased L2-related brain activity in and around the areas mediating L1 such as the LIFG and the STG, and second, the specific engagement of additional brain areas such as areas related to cognitive control (i.e., left prefrontal cortex, ACC, basal ganglia). In the first case, as proposed by [Indefrey \(2006\)](#), L2 speakers may compensate for lower efficiency by driving these regions more strongly and the greater activity observed for L2 may reflect the number of neurons necessary to perform a given task. It is reasonable to suppose that these neural compensatory effects for L2 disappear once a native-like proficiency is achieved. Studies reporting overlapping activity for a highly proficient L2 relative to L1 provide strong theoretical support for [Indefrey's](#) proposal. However, a possible exception to this assumption is given by grammatical processing since it has been shown that, despite native-like L2 proficiency, more extensive brain activity is necessary for L2, localized near the areas mediating L1 grammar ([Wartenburger et al., 2003](#)).

In the second case, the specific engagement of control structures may highlight the nature of L2 processing, with more controlled processing compared to L1 ([Abutalebi & Green, 2007](#); [Rodriguez-Fornells et al., 2006](#)). Again, once native-like proficiency is achieved, a bilingual may rely less on control structures for L2 processing; we may then suppose that L2 is processed in a more 'native-like' fashion. It should be emphasized that these two interpretations are not contradictory. For instance, an L2 speaker could drive the LIFG more strongly during a grammatical task because she/he is in need of more controlled processing. Pertinent to this, recent evidence points also to the non-linguistic functions of the LIFG such as cognitive control ([Koechlin & Jubault, 2006](#); [Koechlin et al., 2003](#)). The greater number of neurons activated could thus be an expression that neurons related to cognitive control within the LIFG are active to support the linguistic functions of the LIFG ([Indefrey \(2006\)](#)).

Finally, the data reviewed on tasks specific to bilinguals such as switching, translation, and language selection show that areas related to cognitive control are necessary to perform such tasks. Again, the role of language proficiency seems to be prominent since less proficient bilinguals activate these areas more strongly. Moreover, because of the engagement of cognitive control areas, it may be postulated that language selection in bilinguals is not language-specific. It is reasonable to argue that both languages may remain active and the selection process involves competition that is resolved with the intervention of these areas (except for circumstances where bilinguals are placed in pure monolingual settings).

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