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Functional neuroimaging and the bilingual brain

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Abstract. The advent of non-invasive neuroimaging techniques opened up a new era in the investigation of language organization in healthy individuals. Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) enabled neuroscientists to examine the mechanisms of cognitive functioning and to probe on-line the close relationship between brain and mind. This is an overview of the most relevant results that have so far been achieved in the field of the cerebral basis of bilingualism by using functional neuroimaging techniques. I will discuss which conclusions may be drawn from these studies considering, in particular, the potential role of a number of variables which have been suggested to play a role in the shaping of language representations in the bilingual brain. Consistent results indicate that second language (L2) proficiency and language exposure and the age of L2 acquisition are very important determinants of the cerebral representation of languages in bilinguals/polyglots. Neuroimaging technologies, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) allow to capture "in vivo" images of the physiology of mind processes. For instance, they show how specific regions of the brain "light up" when subjects are engaged in linguistic activities, such as listening to stories or producing words. Hence, they provide us with a powerful tool for mapping the language faculty in the human brain. The issue of language and brain mechanism becomes more intriguing if we consider the unique capacity of the human brain to acquire, store, and use more than one language. Actually, more than half of the world population speaks more than one language. It becomes clear that related questions deserve serious attention, whether they are theoretical or practical in nature. How do bilingual people understand and produce language? How do people learn and acquire a second language? How does the human brain represent and organize multiple languages? Are there different or overlapping brain areas responsible for the language processes of different languages? And in the case of differential cerebral organization of languages, is this due to the age of second language (L2) acquisition or rather to the degree of L2 proficiency? These are just a few of the many questions that can be raised in this respect. The latter three issues are of particular interest to neuroscientists and may be well addressed with the advances of functional neuroimaging techniques.

Keywords. Bilingualism, Aphasia, Cerebral rapresentation, Age of acquisition.

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Aphasia and bilingualism. Interest for aphasia in bilinguals developed concurrently with the discovery of various language centers in monolinguals, and reflected the numerous controversies about the representation of language in the brain. In particular, it was observed that, if a bilingual subject was affected by an aphasia-related left hemispheric lesion, both languages were not always affected to the same degree. Moreover, the recovery of language, which could follow, was not always parallel for both languages. Many different language recovery patterns have been described (for a classification, see Paradis, 1983): in order to account for patterns of recovery of languages in bilingual aphasia which could be labeled as differential, selective, successive and antagonistic, neurologists have invoked differential cerebral localization for each language.

This hypothetical differential localization of multiple languages in the same brain has invigorated discussion (see for review Paradis 1998 and Fabbro 1999). Some authors argued against an anatomical segregation for multiple languages within the language areas (Penfield 1965). The majority of researchers, however, were inclined to consider various kinds of differential representation including distinct neuroanatomical localization. Segalowitz (1983) argued that it would be surprising if bilingualism had no effect on brain organization and that there are numerous reasons to believe that cerebral representation of language is not entirely the same in polyglots and in monolinguals. Others have proposed that bilinguals are somewhat less lateralized than monolingual speakers, with the right hemisphere prevalently subserving one of the languages of the bilingual (Albert & Obler 1978).

In the late 1970s the “aphasiological landscape” was enriched by electrical cortical stimulation studies of language representation in bilinguals, with temporary inactivation of a brain region (Ojemann & Whitaker 1978). With these techniques, Ojemann and Whitaker mapped naming sites in the lateral cortex of the dominant cerebral hemisphere in bilingual epileptic patients chosen for neurosurgical treatment. In all the patients, each language involved some “common” sites of naming interference and some “specific” areas in which naming was interrupted only for one language. Ojemann postulated that second languages should be organized in a somewhat different manner, their naming areas being generally larger than those for first languages. Calvin and Ojemann (1994) questioned if the occurrence of larger naming sites for the second language was due to lesser knowledge or rather to later acquisition. In psycholinguistics, it is well known that several factors may influence the bilinguals’ performance, among them the age of second language (L2) acquisition, the degree of proficiency in each language, the modality of language learning, and the differential exposure to languages. In general, it was quite difficult to address these issues in clinical studies, mainly because of the well-known limitations of the anatomo-clinical method. Aphasiological studies may demonstrate whether a certain brain region is necessary for a given language component, but not usually the broader system of which that region may form a part. In addition, the kind of anatomical information that can be derived from clinical studies is limited, with lesions that often differ markedly in size and location across different patients. Functional neuroimaging offers a number of advantages over patient studies and lesion-based neuropsychology with regard to understanding the functional organization of the bilingual brain. The advent of noninvasive neuroimaging techniques, as well as the application of electrophysiological techniques such as event-related brain potentials (ERPs) and magnetoencepalography (MEG) makes it more feasible to address crucial questions related to the cerebral organization of multiple languages. The study of healthy bilingual subjects with well-defined language backgrounds and by well-designed paradigms provide a crucial contribution to the understanding of the neural architecture of the bilingual brain.

Functional neuroimaging techniques and their application in neurolinguistics. Functional neuroimaging technologies such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have enabled neuroscientists to examine the human cognitive functioning. If a cognitive process can be sustained for only a few seconds, the snapshot revealed by positron emission tomography (PET) or functional magnetic resonance imaging (fMRI) can show us which parts of the brain are active and to what degree (see Perani & Cappa 1998, for a review). It is generally accepted that regional cerebral blood flow (rCBF) reflects synaptic activity. Local increases in blood flow are necessary to replace the energy consumed by neurons. These changes in regional cerebral blood flow have been demonstrated to be closely related to changes in neural activity in both space and time. In functional neuroimaging studies, images of blood flow are collected in at least two different conditions (e.g., while generating words and while at rest). The perfusion data are then compared in order to find areas where the experimental task is associated with increased cerebral blood flow in comparison with the control task (i.e. rest). These areas of increased perfusion are typically referred to as 'activation foci'.

PET measures blood flow employing radioactive labeled water, specifically hydrogen combined with oxygen (^{15}O), a radioactive isotope of oxygen. The labeled water, which is administered into a vein in the arm, emits copious numbers of positrons as it decays. In just over a minute the radioactive water accumulates in the brain, providing an image of blood flow. The fast decay of ^{15}O and its small amounts permit many measurements of blood flow to be performed in a single session. Each picture serves as a snapshot providing information about the momentary activity of the brain. Typically, images of blood flow are collected before the beginning of a task providing thus a baseline condition (control task) for comparison with those obtained when the brain is engaged in the experimental task. Subtracting blood flow measurements collected during the control task from those associated with the experimental task indicates the parts of the brain active during the latter. Combining functional PET data with the high-resolution anatomical maps produced by MRI provides powerful data sets to investigate structure/ function relationships in the brain.

Functional magnetic resonance imaging (fMRI) is a more recent noninvasive technique, based on the measurement of MRI signals associated with changes in local blood oxygenation levels. The fundamentals of fMRI are well established, being based on a phenomenon known as Blood Oxygenation Level Dependent (BOLD). In response to the neural activation, the rCBF increases in the relevant region; the BOLD effect is particularly manifested in the venous compartment, which is only 60-70% saturated with oxygen at rest and hence has the capacity to get more oxygenated during the activation state, with a corresponding increase in MRI signal intensity (Ogawa, Lee, Kay, & Tank 1990). This totally noninvasive method allows to localize functional brain activation with an accuracy of millimeters and a temporal resolution of about three seconds.

Functional neuroimaging in monolinguals. A large body of functional neuroimaging studies has been devoted to the investigation of language organization in the intact human brain. Briefly, imaging studies employing these techniques did not only largely confirm the anatomical knowledge gained from neuropsychological lesion studies but opened up a number of new perspectives in our understanding of the brain-language relationship. Indeed, most imaging studies underline the importance of classical language-related areas within the perisylvian cortex of the left hemisphere such as Broca's area. However, functional neuroimaging studies have considerably enlarged and redefined the scope of its participation in language processing: The left frontal convexity is involved in many tasks such as word generation (Martin, Wiggs, Ungerleider & Haxby 1996), semantic and phonemic fluency (Mummery, Patterson, Hodges & Wise 1996; Paulesu et al. 1997), semantic monitoring (Thompson-Schill, D'Esposito, Aguirre & Farah 1997), and verbal working memory (Smith, Jonides & Koeppe 1996). Moreover, language-related activation has been reported also outside the classical language areas such as in the inferior temporal gyrus and the temporal pole, the lingual and fusiform gyri (see reviews in Price 1998 and Indefrey & Levelt 2000). Furthermore, right hemispheric activation in mirror regions is observed during the performance of most language tasks. These "language-related" areas, located outside the classical language zone, appear to be specialized for specific components of language processing such as lexical semantics. Noteworthy, the functional role of the language-related areas as revealed by neuroimaging techniques appears to be characterized in terms of linguistically relevant systems such as phonology, syntax, and lexical semantics rather than in terms of activities such as speaking, repeating, reading, and listening (Neville & Bavelier 1998). For instance, a recent neuroimaging experiment of syntax error detection in monolinguals (Moro, Tettamanti, Perani, Donati, Cappa & Fazio 2001) detected the involvement of a selective deep component of Broca's area and a right inferior frontal region in addition to the left caudate nucleus and insula which are activated only during syntactic processing, indicating their role in syntactic computation. These findings provide original *in vivo* evidence that these brain structures in fact constitute an integrated neural network selectively engaged in morphological and syntactic computation.

Functional neuroimaging has also taught us that areas related to linguistic processing in the normal human brain appear to be not only more extended, but also less fixed than previously thought. For example, even when the task and experimental design are held constant, changes in language-related brain activation can be observed as a consequence of increased familiarity with the task. Striking evidence was provided by Petersen, van Mier, Fiez, and Raichle (1998) who investigated the effects of practice on a verbal task using PET. The neural differences putatively related to processing differences between a high and a low practice performance of verb generation were highlighted by this study, in which decreasing brain activity in the left frontal convexity was reported following practice.

Visualizing the bilingual brain. Current research is focused on the degree of functional integration or separation of the languages in the polyglot brain. Several environmental factors have been considered to affect the neural organization of language such as age of language acquisition and degree of proficiency attained in each of the spoken languages.

As to the first factor, a large literature suggests that linguistic abilities are sensitive to the *age of acquisition*. People who learn a language at later ages, particularly after late infancy or puberty, do not generally achieve the same level of proficiency as young learners (Birdsong 1999, Johnson & Newport 1989). The causes of these age effects on language performance are controversial. Explanations range from the postulation of biologically based "critical periods" to differences between infant and adult learning contexts (Lenneberg 1967). In particular, the phonological and morphosyntactic components seem particularly deficient when L2 is learnt later in life, whereas the lexicon seems to be acquired with less difficulty after puberty. This fact may entail the hypothesis that the neural representation of a second language differs as a function of its age of acquisition.

On the other hand, *proficiency* appears to play an important role in L2 organization, too. Several psycholinguistic studies indicate that second language processing changes during the acquisition in late language learners. For instance, in early stages of language learning, lexical items of the second language are processed through association with their translation equivalents in the first language, whereas in later learning stages (and with increased proficiency), processing of second language words is more directly conceptually mediated (Kroll & Stewart 1994, Kroll & Dufour 1995). Thus, detection of the factors that may have a major impact on the cerebral organization of two languages appears to be crucial.

The neuroimaging studies are here divided into two groups: those investigating *language production* (including word repetition) and those investigating *language comprehension* in bilinguals. This broad subdivision is only based on the experimental paradigms used for the imaging studies, which include a number of diverse behavioral tasks, ranging from sentence comprehension to lexical retrieval. While some of these can be clearly considered to focus on input processes or output processes (word generation) respectively, the distinction is not directly applicable to other language domains such as word repetition and judgment tasks. Nonetheless, this atheoretical and, to a certain degree, arbitrary subdivision appears to have interesting implications for the interpretation of language-specific differences of brain activity patterns.

Language production studies in bilinguals. Various functional neuroimaging studies have investigated the neural correlates of language production in bilinguals, as shown in Table 1 (Chee, Tan & Thiel 1999a; Illes, Francis, Desmond, Gabrieli, Glover, Poldrack et al. 1999; Kim, Relkin, Lee & Hirsch 1997; Klein, Zatorre, Milner, Meyer & Evans 1994; Klein, Milner, Zatorre, Meyer & Evans 1995; Perani, Abutalebi, Paulesu, Brambati, Scifo, Cappa et al. 2003; Yetkin, Yetkin, Haughton & Cox. 1996). These studies differ from a methodological point of view, since several authors did not formally investigate the level of proficiency in the second language but divided subjects only on the basis of their age of second language acquisition (see Table 1 for details). A further important variable is that different experimental paradigms and modalities have been used to study language production in bilinguals.

The majority of these studies leave open the possibility that language proficiency, rather than age of acquisition, may be the crucial factor for the neural organization of language processing in bilinguals, as highlighted from language comprehension tasks in Perani and coworkers (1998) in (see below). Along similar lines, the fMRI study of Illes and coworkers (Illes et al. 1999) also included only subjects with a controlled degree of

Table 1. Neuroimaging studies investigating language production in bilinguals.

Study	Task and methods	Group of study	Main results
Klein et al. 1994	Repetition of words in L2 vs. L1 by PET	Homogeneous group of twelve high proficient bilinguals who learned L2 after age five	Increasing activity in the left putamen when repeating words in L2
Klein et al. 1995	PET investigation of phonological and semantic word generation in L1 and L2	Homogeneous group of twelve high proficient bilinguals who learned L2 after age five	No evidence that a language learned later in life may be differently represented from the native language
Yetkin et al. 1996	Word generation in L1, L2 and L3 investigated by fMRI	Non-controlled group of five multilinguals fluent in L2 but not in L3	Greater activity for languages in which subjects were least fluent
Kim et al. 1997	fMRI investigation of sentence generation task in L1 and L2	Non-controlled group of six early bilinguals and six late bilinguals	Common areas of left frontal lobe activation for L1 and L2 in early bilinguals and spatially separated areas for late bilinguals
Chee et al. 1999a	fMRI study of cued word generation in L1 and L2	Controlled group of fifteen early bilinguals and nine late bilinguals, all of them being highly proficient	Similar pattern of brain activations for early and late bilinguals
Illes et al. 1999	fMRI investigation of semantic and non-semantic decisions in L1 and L2	Group of eight late bilinguals (except subject 8) with high degree of proficiency	No differences in brain activity for L1 and L2 during the semantic task
Perani et al. 2003	fMRI investigation of phonologically-cued verbal fluency in L1 and L2	Homogeneous group of early and high proficient bilinguals but exposed differentially to languages	More extensive brain activity for the language to which subjects are less exposed, even when high proficient for that language

language proficiency. All were English-Spanish bilinguals recruited from Stanford University and performed two kinds of tasks: semantic decisions about visually presented words (concrete or abstract), and non-semantic decisions (upper or lowercase type). This study confirmed previous findings (Chee et al. 1999a; Perani et al. 1998): When the degree of proficiency in bilinguals is very high, a common neural network is activated, independent of age of acquisition. Indeed, no differences were found when directly comparing both languages. The main activation foci were found in the left inferior frontal gyrus (Brodmann areas (Ba) 44, 45, 47), with some activation in corresponding areas of the right hemisphere in a few subjects. Interestingly, semantic judgments led to a more extensive pattern of brain activity within those areas than non-semantic judgments.

Recently, a further factor that may be responsible for differential cerebral organization of languages in bilinguals was investigated by Perani et al. (2003), which attempted to assess the effect of "environmental exposure" to one language. This was addressed by studying two groups of early bilinguals with a high degree of proficiency divided on the basis of their language dominance referred to as the language acquired first in life (6 Spanish-born versus 5 Catalan-born). All these subjects were living in Barcelona, Catalonia (Spain) and Catalan was prevalent in their everyday language exposure, as assessed by detailed psycholinguistic investigations. First of all, this study showed that the language acquired first in life, irrespective of language proficiency and age of L2 acquisition, may be an important factor for differences in the bilingual brain, resulting in some differences in brain activation, even in early bilinguals. In particular, the first language engaged less brain areas for the generation of words. One explanation may be that the generation of words in the first language is a more automatic task and is reflected, at the cerebral level, by the engagement of less neural resources. This is in agreement with previous results (Raichle, Fiez, Videen, MacLeod, Pardo, Fox, et al. 1994; Thompson-Shill et al. 1997; Thompson-Schill, D'Esposito & Kan 1999), where a less automatic cognitive task engages more cerebral resources as is the case for the generation of words in the second language in bilinguals.

Another finding from the study of Perani and coworkers (2003) concerned the role of differential exposure to a given language. More extensive brain activation in the left dorsolateral frontal cortex was found in the group of Catalans when generating words in Spanish as compared to the group of Spaniards generating words in Catalan. These findings suggest that a second language associated with lower environmental exposure is in need of additional neural resources in comparison to L1 (i.e., Spanish language in Catalans). On the other hand, the group of Spaniards with a good exposure to Catalan had a reduced area of brain activation for word generation in L2. The authors hypothesized that the brain activations are related to exposure and practice. The brain might then eventually support the generation of words with less or more recruitment of cerebral structures.

Before attempting to draw some conclusions on the results of production studies, several limitations of the available evidence must be acknowledged. The majority of the production experiments in bilinguals are based on single word processing, in particular in word generation (fluency) tasks. Fluency tasks are associated with the same pattern of brain activation found previously in monolinguals, namely, involvement of the left dorsolateral frontal cortex (Poline et al. 1996). The generation of words according to a cue is a complex task, which involves multiple cognitive processes such as lexical search, lexical retrieval, and speech production. Anatomo–functional differences have been reported between fluency tasks, for example between phonemic verbal fluency and semantic verbal fluency (Paulesu et al. 1997, Mummery et al. 1996). Functional studies of brain representation of different languages should take account of these cognitive aspects.

From the published results we may draw the following conclusions: there are no differences in brain activity for very early bilinguals (we might assume that these subjects were highly proficient for both languages) and, similarly, no differences for late bilinguals, if they are highly proficient in both languages (Chee et al. 1999a, Illes et al 1999, Klein et al. 1995). In contrast with this assumption is the study of Kim and coworkers (Kim et al. 1997) in which spatially separated regions were activated within Broca's area for L1 and L2. However, as this study lacks information about the degree of proficiency in L2 of the subjects, we do not know whether this differential cerebral organization is a consequence of the age of second language acquisition or rather of a reduced proficiency. This criticism is also applicable to Yetkin et al.'s study (1996), even if they provide evidence that when a language is spoken less fluently, a larger cerebral activation can be observed in comparison with more fluent languages. We do not know, however, if this result must be ascribed to high/low proficiency or high/low exposure.

Overall, these findings appear to indicate that attained proficiency might be more important than age of acquisition as a determinant of the cerebral representation of language production in bilinguals/polyglots. Moreover, the results of the study by Perani et al. (2003) underline that even small differences in age of acquisition and environmental exposure to a language may account for functional modulation in the cerebral representation of L1 and L2.

Language comprehension studies in bilinguals. Many studies have investigated the brain correlates of language comprehension in bilinguals. These studies are listed in Table 2. Perani and colleagues carried out several PET studies in which they investigated the receptive sentence processing of late low proficiency bilinguals (Perani, Dehaene, Grassi, Cohen, Cappa, Dupoux et al. 1996), early high proficient, and late high proficient bilinguals, respectively (Perani, Paulesu, Sebastian-Galles, Dupoux, Dehaene, Bettinardi et al. 1998). In the first, Perani and coworkers (1996) used PET to study nine late acquisition bilinguals (Italian - English) who had low-proficiency in their second language, English, which they had studied at school for at least five years. None of the subjects had spent more than one month in an English-speaking environment and they, therefore, mastered L2 poorly. Partially different cerebral substrates were active for the first and second language when compared to the baseline condition (attentive rest condition). Areas activated by the first language comprised left perisylvian areas, including the angular gyrus (Ba 39), the superior and middle temporal gyri (Ba 21 and 22), the inferior frontal gyrus (Ba 45) and the temporal pole (Ba 38). Several homologous areas (Ba 21, 22 and 38) were also activated in the right hemisphere. In contrast, the set of active language areas was considerably reduced when applying the same analysis to the second language. Specifically, only the left and right superior and middle temporal areas remained active. One of the crucial areas of differential activation was, rather unexpectedly, the temporal pole. Activation of this region has been seldom reported in the functional imaging studies on language and memory. However, some studies have shown that the anterior part of the temporal lobe is activated by tasks requiring listening or reading sentences or a continuous text (Bottini, Corcoran, Sterzi, Paulesu, Schenone, Scarpa et al. 1994; Fletcher, Happé, Frith, Baker, Dolan, Frachowiak et al. 1995; Mazoyer Tzourio, Frank, Syrota, Murayama, Levrier, Salamon et al. 1993; Perani et al. 1996), rather than unconnected verbal material. Perani and coworkers suggested that these regions might be involved in processes associated with the sentence or even the discourse level, such as integration with prior knowledge, inference, and anaphoric reference. In addition, the temporal poles might be recruited on the basis of increasing memory demands, when the subjects are engaged in the natural task of listening to some simple narrative.

In the second experiment (Perani et al. 1998), the authors tested Italian native speakers who learned English after age ten, who had spent one to six years in an English speaking country, and who currently used English in their daily activities. These “late” bilinguals were scanned during experimental conditions such as listening to Italian, English, or Japanese stories (unknown to all subjects), or attentive silence.

The overlapping pattern of activation for L1 and L2 in Perani et al. (1998) contrasted to the considerable differences in L1 - L2 activations found in low proficiency speakers (Perani et al. 1996). The combined

Table 2. Neuroimaging studies investigating language comprehension in bilinguals.

Study	Task and Methods	Group of Study	Main Results
Perani et al. 1996	Passive listening to stories in L1, L2 and in a third unknown language as studied by PET	Homogeneous group of nine low proficient late bilinguals	Greater activations when processing the native language in comparison to L2
Dehaene et al. 1997	fMRI single subject study of listening to stories in L1 and L2	Homogeneous group of eight low proficient late bilinguals	Differential brain activation for late L2 learners (including the right hemisphere)
Perani et al. 1998	Two PET studies of two groups of subjects listening to stories in L1 and L2	Two homogeneous groups of bilinguals: nine high proficient but late bilinguals and 12 high proficient but early bilinguals	Overlapping patterns of brain activity in all high proficient bilinguals, underlining the crucial role of proficiency
Chee et al. 1999b	fMRI investigation of visually presented sentence-comprehension in L1 and L2	Homogenous group of fourteen early bilinguals	Common patterns of brain activity for L1 and L2
Price et al. 1999	Single word comprehension in L1 and L2 by PET	Homogenous group formed by six late bilinguals	Greater activity in the left temporal lobe for L1
Chee et al. 2001	fMRI scanning while bilinguals perform semantic judgments	Two homogenous groups of low proficiency and high proficiency bilinguals	Reduced brain activity in left prefrontal and parietal regions when subjects were highly proficient
Wartenburger et al. 2003	fMRI investigation of grammatical and semantic judgment in bilinguals	Three controlled groups of bilinguals divided on the basis of age of L2 acquisition and proficiency	Age of acquisition dependency of grammar and proficiency dependency of semantic judgments

results of these studies provided the first in vivo evidence for a different functional representation of L1 and L2 in comprehension, when a crucial variable such as language proficiency is taken into account.

Dehaene et al. (Dehaene, Dupoux, Mehler, Cohen, Paulesu, Perani et al. 1997). performed a similar experiment by fMRI in a comparable group of experimental subjects (eight late bilinguals, with French being the first language and English the second language) scanned while listening to short stories alternatively in French and English. Listening to the stories in L1 engaged a set of left-sided brain areas with, in addition, similar although much weaker, activation in the right hemisphere, whereas this pattern radically changed when subjects processed their second language. It is noteworthy that a single subject analysis showed a quite disparate pattern of brain activity for L2, indicating large intersubject variability. Indeed, listening to L2 engaged a highly variable network of left and right temporal and frontal areas among the subjects, in some individuals restricted only to the right hemisphere. On the basis of these results, the authors confirmed that while the processing of the first language essentially relies on a dedicated left hemispheric cerebral network, the processing of a second language acquired late in life and mastered with reduced proficiency, may be differentially organized.

This series of experiments (Dehaene et al. 1997, Perani et al. 1996, 1998) provides evidence of functional modulation in the network that mediates language comprehension in the bilingual brain. The main result is that, while listening to stories in L1 and in L2 yields very different patterns of cortical activity in low proficiency subjects, no major differences are present in highly proficient subjects, even with later L2 acquisition. The languages spoken by the low and high proficiency volunteers were identical, and so was the procedure. Hence we must conclude that the degree of mastery of L2 is responsible for the observed differences between these late acquisition groups: auditory language comprehension in proficient bilinguals who have learned L2 after the age of ten relies upon a macroscopic network of areas that is similar for L1 and L2 groups. It is noteworthy that these results were confirmed also by two further studies (Chee, Caplan, Soon, Sriram, Tan, Thiel et al. 1999b; Price, Green & von Studnitz 1999).

The study of Price et al. (1999), in which six late bilinguals were investigated using PET, provided results at the single word level. The language areas in the left temporal lobe were more activated when processing the first language compared to a less known language. Indeed, comprehension of words in L1 yielded a greater activation in the temporal pole than comprehension of the words in L2. This is in agreement with Perani et al.'s (1996) results in late bilinguals with a low degree of proficiency.

In conclusion, in *early bilinguals*, who received equal practice with their two languages from birth, a single and common language system appears to be responsible for the processing of both languages (Chee et al. 1999b, Perani et al. 1998). This system extends along a left-sided network, comprising all the classical language areas. In the temporal lobe these include the superior and middle temporal gyri, the angular gyrus, and the temporal pole, a structure that seems specifically engaged by sentence and discourse level processing. In the case of late bilinguals, the degree of language proficiency seems to be a critical factor in shaping the functional brain organization of languages, since *high-proficient* late bilinguals activated strikingly similar left hemispheric areas for L1 and L2 (Chee et al. 1999b, Perani et al. 1998), whereas *less proficient* subjects have different patterns of activation for their two languages (Chee et al. 2001, Dehaene et al. 1997, Perani et al. 1996, Price et al. 1999). In the case of comprehension of extended text (listening to stories), the activation was more limited in the case of L2. This may reflect a less consistent pattern of activation (as suggested by the results of Dehaene' s study), or a more limited processing, focusing on a superficial analysis of the less proficient language. Also in the case of comprehension, increasing language proficiency appears to be a crucial factor for language representation in bilinguals.

We should at this point underline that the paradigms employed so far with functional imaging in language studies do not allow a clear differentiation of the various language components (semantic, morphological, and syntactic), as traditionally defined within linguistic theory. For instance, there is an ongoing discussion whether there is a "critical period" in second language (L2) acquisition (Johnson & Newport 1989) and whether this period concerns only the phonological and morphosyntactic domains of language processing. Using event-related potentials (ERPs), Weber-Fox and Neville (1996) found that different aspects of language (i.e., semantic and syntax) are differentially affected by the age of second language acquisition. To address this issue, a recent fMRI study investigated the neural correlates of grammatical and semantic judgments in three groups of Italian-German bilinguals. The subjects had acquired the first and second language from birth (first group) or after the age of six, but with different proficiency levels (second and third group) (Wartenburger, Heekeren, Abutalebi, Cappa, Villringer & Perani 2003). This study demonstrates that age of acquisition specifically affects the cortical representation of grammatical processes. Only in the case of the second language acquired very early in life, overlapping neural substrates for L1 and L2 grammar result. In addition, in late bilinguals proficiency is the main determinant of the cerebral organization of both grammar and semantics. These findings are in agreement with the existence of a 'critical period' for language acquisition and suggest that grammatical processing, given its dependence on age of acquisition, is based on competence which should be neurologically 'wired-in'.

Conclusions. Several factors, which were shown to be crucial in psycholinguistics, may affect the neural basis of the bilingual language system. These factors are mainly represented by the age of L2 acquisition, the degree of proficiency for languages and the degree of usage/exposure to languages. The available evidence suggests that proficiency is the most relevant one. In the case of language production tasks in general and in tasks of language comprehension, there are differences which appear to go in opposite directions: more extensive cerebral activations being associated with production in the less proficient language, smaller activations with comprehension of the less proficient language. Hence, it may be speculated that this puzzling result may reflect the inherent differences of these aspects of linguistic processing. In the case of "effortful" tasks such as word generation, this difference may be attributed to the recruitment of additional resources. On the other hand, in the case of sentence comprehension, the automatic nature of the processing may be reflected in a more limited elaboration of the linguistic material in the less proficient language. Another possibility, suggested by the single subject study of Dehaene et al. (1997) is the large intersubject variability in the activation pattern for comprehension of L2. It must be underlined that the neuroimaging data do not question the claim that age of acquisition is a major determinant of proficiency in L2. Many linguistic and neurophysiological studies have found that late learners are typically less proficient than early learners (Flege, Munro & MacKay 1995; Johnson & Newport 1989; Weber-Fox & Neville 1996). The role of age of acquisition seems to have crucial implications for particular domains of language such as grammar, as shown by the study of Wartenburger and coworkers (2003).

The specific role of practice and exposure in terms of frequency of usage has to be further investigated and should not be confounded with proficiency (in terms of absolute level of fluency). The finding that language exposure may be an additional crucial factor for the neural representation of multiple languages (Perani et al. 2003) may provide important inputs either to educational fields, such as in the case of second language learning, as well as to language rehabilitation in bilingual aphasia.

The most important contribution of imaging studies of bilingualism to our understanding of language representation in the brain is the observation of aspects of invariance and aspects of plasticity. We can conclude from the available evidence that the patterns of brain activation associated with tasks which engage specific aspects of linguistic processing are remarkably consistent across different languages and different speakers. These relatively fixed patterns are however clearly modulated by a number of factors, which have been analytically addressed in this review. Future studies are expected to disentangle the specificity and selectivity of these interactions. In general, the imaging study of multilingual subjects appears to be a promising model for the study of the interactions between a pre-wired neurobiological substrate and environmental, time-locked influences.

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