The neural basis of first and second language processing
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Fundamental breakthroughs in the neurosciences, combined with technical innovations for measuring brain activity, are shedding new light on the neural basis of second language (L2) processing, and on its relationship to native language processing (L1). The long-held assumption that L1 and L2 are necessarily represented in different brain regions in bilinguals has not been confirmed. On the contrary, the available evidence indicates that L1 and L2 are processed by the same neural devices. The neural differences in L1 and L2 representations are only related to the specific computational demands, which vary according to the age of acquisition, the degree of mastery and the level of exposure to each language. Finally, the acquisition of L2 could be considered as a dynamic process, requiring additional neural resources in specific circumstances.

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Introduction
During the past few years, a large body of neuroimaging and neurophysiological studies has been devoted to the study of the neural organization of language. To date, the results of positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and event-related potential (ERP) studies have not only converged with the findings of clinical aphasiology but have also opened several new perspectives to our understanding of the brain–language relationship.

There has been increasing attention to the role of cortical regions that are outside the traditional left perisylvian areas in language processing [1,2]. Within these networks, specific frontal, temporal and parietal regions, together with subcortical structures, are differentially involved in specific aspects of linguistic computation, from word-level to sentence processing [3,4] modern concept of brain functional specialization that emerged as a consequence of the development of sophisticated experimental paradigms in functional neuroimaging and neurophysiology enables the study of language subcomponents, such as phonology, syntax and lexical semantics, together with their computational processing demands. The use of refined experimental tasks, rather than of verbal activities, such as speaking and listening, has played a crucial part in the characterization of linguistically relevant systems [1,3].

In recent years, functional techniques for measuring brain activity have also shed new light on the neural basis of second language (L2) processing and its relationship to native language processing (L1). A basic issue in this area is whether a L2 learnt later in life can be processed through the same neural mechanisms underlying L1 acquisition and processing. Considering that L1 is acquired implicitly, and mediated, according to many theorists, by innate learning mechanisms triggered during a critical period, it remains an open question as to whether or not the same mechanisms underlie the acquisition of L2.

A recent theory claims that the processing of L2 acquired late in life depends upon different cognitive mechanisms and cerebral structures from L1 [5]. Following this view, grammatical knowledge for L2 is declarative rather than implicit, as is the case for L1 grammar. By contrast, lexical knowledge is represented in the declarative memory system for both L1 and L2. Because implicit and declarative knowledge are mediated by distinct neural systems (a left frontal-basal ganglia circuit for implicit knowledge and left temporal language areas for declarative knowledge), Ullman’s differential hypothesis claims that L2 acquisition in adulthood could not depend on the same brain mechanisms that are used to process the native language [5].

Brain imaging offers a unique opportunity to assess directly the representation of L2 subcomponents in the bilingual brain. The results have so far contradicted Ullman’s hypothesis [6∗∗,7,8∗]. In particular, during grammatical tasks in bilinguals the brain structures traditionally associated with grammatical processing (e.g. Broca’s regions, basal ganglia) were involved at a comparable level when performing the tasks in both L1 and L2. Additional activation for L2, extending into areas adjacent to the areas subserving L1 grammar, was evident only in bilinguals with low proficiency and/or late acquisition. These results indicate the effects of variables, such
as the age of L2 acquisition and proficiency, on the pattern of brain activation in bilinguals.

In the present review we focus on studies that show how several factors, such as the age of acquisition, degree of proficiency and exposure to L2, affect the neural organization of L2.

The neural organization of L2 processing
Since its inception, neuroimaging work on bilinguals has been motivated by the same ‘localizationist’ questions that run through the bilingual aphasia literature: whether multiple languages are represented in overlapping or in separate cerebral systems. For instance, in bilingual aphasics the observation of selective recovery of one language was often interpreted as evidence for differential neural representation of languages [9]. However, there are limitations to the generalization of such lesion evidence to neurologically healthy individuals [10,11]. In addition, neuroimaging and neurophysiological data on this issue have often been influenced by possible biases, such as lack of information on the age of acquisition and degree of proficiency in the experimental subjects. Both these variables indeed exert profound influences on the brain organization of L2 [10].

One the one hand, according to psycholinguistic evidence grounded on the concept of ‘universal grammar’, the age of L2 acquisition is expected to be crucial for grammatical processing. In fact, grammatical processing is particularly deficient when L2 is learned later in life [12]. On the other hand, lexical–semantic processing seems to be less affected by age of acquisition, but rather to depend on the degree of L2 proficiency [6**].

It is likely that other factors, such as usage and exposure to a given language, can affect brain plasticity mechanisms, leading to modifications of the neural substrate of language. Here, we consider separately how these variables might influence L2 processing.

Is age-of-L2 acquisition fundamental for the neural organization of L2?
An ongoing issue in neurobiology concerns the fact that the acquisition of language seems to depend on appropriate input during a biologically based ‘critical period’ [13]. It has also been suggested that L2 learning might be subject to such crucial time-locked constraints [12]. However, L2 can be acquired at any time in life, although L2 proficiency is rarely comparable to L1 if L2 is acquired after the critical periods [12,13]. The dependence of grammatical processing upon these age effects was confirmed by early ERP studies [14] and by recent functional brain imaging studies [6**]. In particular, Wartenburger et al. [6**] observed no differences in brain activations for grammar in L1 and L2 in very early (from birth) proficient bilinguals. Conversely, late (L2 acquisition after age 6) but highly proficient bilinguals were in need of additional neural resources to achieve a comparable native-like performance in grammatical tasks (Figure 1). The same did not apply to lexical–semantic processing, for which the only difference in the pattern of brain activity in bilinguals appeared to depend upon the level of attained proficiency [6**]. Notably, the additional brain activity during grammatical processing in these late bilinguals (as compared with the very early bilinguals) was only found in language-related regions, such as Broca’s area. This emphasizes the fact that L2 processing is carried out

**Figure 1**

Brain activity patterns during grammatical processing in L2 as compared with those in L1 in three different groups of Italian–German bilinguals with different ages of L2 acquisition and levels of L2 proficiency. Whereas early bilinguals (EAHP: early acquisition, high proficiency) engaged for both languages the same neural structures (no activation differences in the brain rendering), this does not apply for late bilinguals. Both groups of late bilinguals, with high or low proficiency (LAHP: late acquisition, high proficiency; LALP: late acquisition, low proficiency), engage more extended neural substrates in inferior frontal and parietal regions for grammatical processing in L2. These results emphasize the effect of age of acquisition on the neural underpinnings of grammatical processing (modified from Wartenburger et al. [6**]).
through the same brain computational devices as those in L1 processing.

Similar findings have been reported in studies directly addressing L2 acquisition. For instance, Friederici et al. [15] provided ERP evidence for a real-time pattern of brain activation similar to that in L1 in the acquisition of L2 syntax during adulthood. Likewise, using fMRI Sakai et al. [8] showed that the acquisition of grammatical competencies in late bilingual twins was achieved through the same neural systems for processing L1 grammar. Two further fMRI studies in adults reported comparable evidence for shared computational brain devices underlying native language and the acquisition of L2 grammar [16,17]. In particular, Musso et al. [17] 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.

All these studies emphasize the fact that grammatical processing of L2 is acquired and carried out through the same computational brain devices underlying L1 grammatical processing. There are differences in terms of additional resource demands, but these are within the same neural system.

Language proficiency and L2 brain organization

As mentioned above, the degree of language proficiency seems to exert a more pervasive influence on the lexical–semantic level of L2. According to psycholinguistics, during the early stages of L2 acquisition there might be a dependency on L1 to mediate access to meaning for L2 lexical items [18]. As L2 proficiency grows, this dependency disappears. Greater levels of proficiency in L2 produce lexical–semantic mental representations that more closely resemble those constructed in L1. According to Green’s ‘convergence hypothesis’ [19], any qualitative differences between native and L2 speakers disappear as proficiency increases. The convergence hypothesis claims that the acquisition of L2 arises in the context of an already specified, or partially specified, system, and that L2 will receive convergent neural representation within the representations of the language learned as L1.

Whether word or sentence production, or word completion, were used as experimental tasks, neuroimaging studies reported common activation in the left hemisphere when the degree of L2 proficiency was comparable with that for L1 [20,21]. This happened irrespective of the differences in orthography, phonology and syntax among languages [20]. Conversely, bilinguals with low proficiency in L2 engaged additional brain activity, mostly in prefrontal areas [7,22]. Similar results were also found in studies that did not directly address lexical retrieval, but employed judgment tasks in the lexical–semantic domain [6,23,24].

Proficiency-related neuroanatomical differences were also reported in language comprehension tasks. In that specific case, low proficient bilinguals, when compared with highly proficient bilinguals, activated less neural substrate for sentence- and discourse-level processing in the left temporal lobe [25].

The role of exposure and usage of L2

Plasticity after brain damage in the adult human brain has been repeatedly observed in sensory and motor pathways and has also been suggested for language systems during recovery from aphasia [26]. Very little is known about the effect of environmental input in shaping the neural organization of L2.

The study of bilinguals with increasing L2 proficiency might offer a suitable model to test the neural effects of...
environmental input. For example, the neural differences between low and high proficient bilinguals during word generation tasks [7,20–22] provide strong evidence for brain plasticity. When proficiency increases, L2 processing ‘converges’ on to the neural representation of L1 [19].

Notably, direct evidence for plasticity was reported also in the case of differential exposure to L2, in terms of L1 and L2 daily usage [27*]. Perani et al. [27*] showed that differential exposure to a given language might affect the cerebral representations in multilinguals, even when the degree of proficiency is kept constant (Figure 2). 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 [28].

Pallier et al. [29] addressed the question of whether or not L2 can replace L1 in Korean subjects adopted during childhood. These subjects had not been exposed to their L1 from infancy; behavioral and fMRI findings in a speech perception task suggested that indeed L2 might replace L1.

Direct structural evidence for plasticity has been recently provided using voxel-based morphometry techniques [30**]. In early acquisition highly proficient bilinguals, there was an increase in grey matter density in the inferior parietal cortex that also correlated with L2 proficiency. These striking results fit with data from the classical aphasiological literature, suggesting that the left inferior parietal lobe is the site of the so-called ‘language talent’ in polyglots [31].

**Conclusions**

The available evidence supports a dynamic view of the neural basis of L2 processing. The most important contribution of brain imaging studies to the neurobiology of language in bilinguals is the observation of both invariance and plasticity. First, concerning language acquisition, L2 seems to be acquired through the same neural devices responsible for L1 acquisition. Second, regarding L2 processing, the patterns of brain activation associated with tasks that engage specific aspects of linguistic processing are remarkably consistent among different languages, which share the same brain language system. These relatively fixed brain patterns, however, are modulated by several factors. Proficiency, age of acquisition, and amount of exposure can affect the cerebral representations of each language, interacting in a complex way with the modalities of language performance. Future studies disentangling the different language processes should always take into account these potentially important variables.

Furthermore, neuroimaging studies on the neural basis of L2 processing might benefit from longitudinal investigations addressing the natural course of L2 acquisition (i.e. follow-up studies in L2 teaching classrooms). They might provide a neurobiological evidence-based contribution to language educational fields. Language acquisition has mostly been documented in the context of artificial languages that are learnt within brief time periods. Although studies focusing on artificial language acquisition are very informative [32*] they do not represent the natural course and environment of L2 acquisition.

**References and recommended reading**

Papers of particular interest, published within the annual period of review, have been highlighted as:

- of special interest
- of outstanding interest


The authors present the first fMRI study demonstrating that the age of L2 acquisition is crucial for grammatical processing. Grammatical and semantic judgments in three groups of Italian–German bilinguals were addressed with fMRI. Subjects in this study acquired L1 and L2 from birth (first group) or after the age of 6 years, but with different proficiency levels (second and third group). Only in the case of the L2 acquired very early in life did the neural substrates for L1 and L2 grammatical processing overlap. Thus, this suggests that grammatical processing, given its dependence on age of acquisition, is based on competence that is neurologically ‘wired-in’. In addition, proficiency is the main determinant of the cerebral organization of both grammar and semantics in late bilinguals.


The authors investigated, using fMRI, new L2 learners at a secondary education school in Japan. Twins were used as subjects to investigate whether or not 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 as part of their standard classroom education. The authors reported 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. These findings suggest a cortical mechanism underlying L2 acquisition that crucially depends on shared genetic, neural and environmental factors.


The effect of ‘environmental exposure’ to L2 was addressed in this fMRI study in two groups of early high proficient bilinguals living in Barcelona (either Spanish-born or 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).


In this study, structural plasticity in the bilingual brain was investigated by whole-brain voxel-based morphometry in healthy right-handed English and Italian bilinguals. Differences between monolinguals and bilinguals were found in the neural density of the left inferior parietal lobe. Early bilinguals had increased grey matter density within this area. Notably, late bilinguals might also have comparable grey matter density in this brain area, but only when L2 proficiency is high.


This study investigated artificial language learning during fMRI scanning in adults. Increased proficiency for the artificial language was associated with decreased left hippocampal activity but increased recruitment of Broca’s area, indicating a learning-related change in brain circuitry underlying relational processes of language learning, with a transition from a similarity-based learning system in the medial temporal lobes to a language-related processing system in the left prefrontal cortex.