

# The Role of Age of Acquisition and Language Usage in Early, High-Proficient Bilinguals: An fMRI Study During Verbal Fluency

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**Abstract:** We assessed the effects of age of acquisition and language exposure on the cerebral correlates of lexical retrieval in high-proficient, early-acquisition bilinguals. Functional MRI was used to study Spanish–Catalan bilinguals who acquired either Spanish or Catalan as a first language in the first years of life. Subjects were exposed to the second language at 3 years of age, and have used both languages in daily life since then. Subjects had a comparable level of proficiency in the comprehension of both languages. Lexical retrieval with the verbal fluency task resulted in the well-established pattern of left hemispheric activation centered on the inferior frontal region. The effect of age of acquisition was assessed by dividing the subjects into two groups, on the basis of the language acquired first (Catalan-born or Spanish-born bilinguals). Functional comparisons indicated that less extensive brain activation was associated with lexical retrieval in the language acquired earlier in life. The two groups were also different in language usage/exposure, as assessed with a specific questionnaire; in particular, the exposure to the second language (Spanish) was less intensive in the case of Catalans. This was reflected in a significant interaction, indicating a more extensive activation in Catalans during production in Spanish. Overall, these results indicate that, during a production task, both age of acquisition and language exposure affect the pattern of brain activation in bilinguals, even if both languages are acquired early and with a comparable level of proficiency. *Hum. Brain Mapping* 19:170–182, 2003. © 2003 Wiley-Liss, Inc.

**Key words:** language acquisition; bilinguals; functional neuroimaging

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## INTRODUCTION

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The effect of environmental input in shaping the neural organization of language is controversial. At a general level, modifications of cerebral language representation due to external influences may be considered as an instance of cerebral plasticity (Neville and Bavelier, 1998). While plasticity after brain damage in the adult human brain has been repeatedly observed in sensory and motor pathways (Donoghue, 1995), functional reorganization involving the language ar-

eas has only been suggested by studies of recovery from aphasia (Weiller et al., 1995). The study of the cerebral organization of language representation in bilinguals may provide another model to test this hypothesis.

Several environmental factors have been considered to affect the neural organization of language, such as the age of second language (L2) acquisition and the degree of proficiency attained in each of the spoken languages. As for the first factor, a large literature suggests that linguistic abilities are sensitive to the age of exposure to language. People who learn a language later, particularly after late infancy or puberty, do not generally achieve the same level of proficiency as young learners (Birdsong, 1999; Johnson and Newport, 1989). The causes of these age effects on language performance are controversial, with explanations ranging from the postulation of a biologically based "critical period" for language acquisition, to an emphasis on differences between infant and adult learning contexts (Lenneberg, 1967). The performance differences may entail the hypothesis that the neural representation of a second language differs as a function of its age of acquisition.

Furthermore, proficiency appears to play an important role in L2 organization. Several psycholinguistic studies have shown that, with increasing proficiency, the mental processing of L2 changes in late language learners. For instance, in initial stages of L2 acquisition, lexical items of the second language are processed by directly translating them through their equivalents in the first language, whereas in later learning stages, when proficiency increases, they become more concept-mediated without translation (Dufour and Kroll, 1995; Schreuder and Weltens, 1993). Hence, first language and second language lexical items are thought to access a common semantic system, as a bilingual becomes more proficient in the second language. Thus, it may be expected that also the increasing proficiency of late learners should entail a reorganization of language areas in the bilingual brain.

Only a few functional neuroimaging studies in bilinguals have specifically addressed these interesting issues (Chee et al., 1999a,b, 2001; Dehaene et al., 1997; Illes et al., 1999; Kim et al., 1997; Klein et al., 1994, 1995; Perani et al., 1996, 1998; Price et al., 1999). The results of these neuroimaging studies were recently summarized (Abutalebi et al., 2001). The conclusion drawn was that second languages learned later in life (after age 6–9) and with less attained proficiencies appeared to be associated with non-overlapping, less reproducible cerebral substrates within groups of bi-

linguals, compared to the relatively fixed left-hemispheric network observed in groups of monolinguals. On the other hand, when proficiency was kept constant in these studies, age of acquisition per se did not seem to have a major impact on brain representations of L2, at least at the macroscopic (brain area) level. Specifically, in the case of word generation and, in general, of production tasks, there was some evidence that a lower degree of language proficiency may be associated with differences in brain activity in anterior brain structures, such as Broca's area and the basal ganglia (Chee et al., 1999a; Yetkin et al., 1996). Conversely, in the case of comprehension, the proficiency-related differences involved the temporal lobes, in particular the temporal pole (Dehaene et al., 1997; Perani et al., 1996, 1998). A crucial finding highlighted by these studies is that the differences appeared to go in different directions: more extensive cerebral activations being associated with production in the less proficient language, smaller activations when comprehending the less proficient language. It was hypothesized that, in the case of effortful tasks (such as word generation), this difference may be attributed to the recruitment of additional resources. In the case of language comprehension, the less extensive activation associated with the less proficient language may reflect a more limited elaboration of the linguistic material (Abutalebi et al., 2001).

None of the imaging studies have taken into consideration the role of environmental exposure on cerebral language representation, or its relationship to the first and second language in early bilinguals. It is well known from psycholinguistic studies that exercise, usage, and experience may increase performance in L2 production and comprehension (Green, 1998). All this is applicable to late bilinguals, and all late bilingual speakers are well aware of these phenomena.

Keeping this in mind, our aim was twofold. We sought first to investigate any differences in brain activation in early, high-proficient bilinguals who master both languages very early in life but with different age of acquisition; in previous studies, a possible subtle effect of age of acquisition may have been obscured by the large effect of the proficiency level. Second, we investigated the functional effect on neural representations of differential language usage in everyday life.

Using functional magnetic resonance imaging (fMRI), we addressed these issues in a group of well-defined, early-acquisition, high-proficiency bilinguals by evaluating the cerebral pattern of activation during lexical search and retrieval. The language learned first was defined as L1, and the language usage/exposure

was determined by means of measurements in different daily contexts. These environmental factors may be considered crucial in affecting the neural organization of language. Their possible effect on the cerebral language representation has never been assessed using functional neuroimaging.

The participants (six Spanish-born and five Catalan-born bilinguals) acquired either Spanish or Catalan as the first language in the first years of life. They were exposed to the second language after the age of 3 years, and since then they have used both languages in their daily lives. Indeed, the subjects all live in Barcelona (Catalonia, Spain), which is a highly bilingual society where Catalan and Spanish languages are both used in social contexts. The groups differ in terms of the amount of daily L2 usage (either Catalan or Spanish being more prevalent in everyday life), as assessed by formal investigation. The two groups had a comparable level of proficiency in language comprehension.

## SUBJECTS AND METHODS

### Subjects

Eleven healthy, right-handed subjects (as verified using the Edinburgh Inventory; Oldfield, 1971) participated in this study. This group included men (age range, 20–27 years) from a naturally bilingual society, in which highly skilled bilinguals represent a large proportion of the population. All subjects were recruited on a voluntary basis and gave written, informed consent. The experimental protocol followed the guidelines for human research developed by ethical committees of the participating institutions and conformed to the Helsinki Declaration.

### Subject selection and behavioral evaluation

Subjects were chosen from a pool of more than 80 subjects who were selected through behavioral tests and directed interviews at the University of Barcelona. These screening tests were designed to find bilinguals who fulfilled the following criteria: (1) both languages acquired in early childhood, and (2) both languages spoken equally well since acquisition. In the first round of subject selection, participants were asked questions concerning the languages they were exposed to in the very first years of life, i.e., languages spoken (to them) by the father, mother, brothers, sisters, and if any other person was living in their home (e.g., grandmother). Only participants exposed exclusively to one language (either Spanish or Catalan)

during the first years of life (before age 3) were selected. Effectively, participants were raised as monolinguals until age 3 years. All subjects acquired the second language after the age of 3 (when they attended kindergarten), and since then they have used both languages and are highly proficient in both. In the second round of subject selection, the level of proficiency in native and second language was formally assessed (see Perani et al., 1998).

The participants were asked to specify, using a detailed questionnaire, their present use of each language. They were asked to estimate how many hours per day they were exposed to each language. The questionnaire covered the following areas: media (TV and radio), family (with each member), university (classmates and teachers), friends (not classmates), girlfriend, reading (newspapers and books), other activities (hobbies, sports, music, etc.) (see Table I).

### Scanning procedures

MRI scans were performed on a 1.5 T General Electric Signal Horizon System (GE, Milwaukee, WI), equipped with echo-speed gradient coils and amplifier hardware, using a standard quadrature head-coil. Before fMRI scans, scout spin-echo sagittal scans (flip angle 90 degrees, TE = 20 msec, TR = 500 msec, FOV = 240 × 240 mm, matrix 256 × 192) were acquired to visualize the anterior and posterior commissures on a midline sagittal section and to facilitate data acquisition roughly along the bicommissural plane. A structural spin-echo data set matched to the fMRI images (TE = 20 msec, TR = 600 msec) was also acquired, prior to fMRI data collection, in order to facilitate subsequent stereotactic normalization with SPM software of the MRI images. Field homogeneity was adjusted by means of “global shimming” for each subject.

Activation images were acquired using an echo planar imaging (EPI) gradient echo sequence (flip angle 90 degrees, TE = 60 msec, TR = 3,000 msec, FOV = 280 × 280, matrix 64 × 64). The selected volumes consisted of 24 contiguous transverse images, 4-mm thick, which were acquired every 3 sec. The volume matrix was then resampled to 64 × 64 × 24 resulting in a final voxel size of 4.375 × 4.375 × 4 mm.

### Image processing

After image reconstruction, raw-data visualization and pre-processing were performed with Analyze-5 software (BRU, Mayo Foundation, Rochester, MN). All subsequent data analysis was performed in Matlab

**TABLE IA. Total everyday exposure to Catalan language, by daily activity**

Subject	TV	Radio	Teacher	Classmates	Family	Friends	Fiancée	Hobby	Reading	Exposure to Catalan
L1: Catalan										
X.S.	15.70	0.41	17.71	5.31	33.06	11.81	0.00	4.13	4.72	92.85
B.P.	9.28	0.00	9.94	1.66	15.47	5.52	19.34	1.33	2.32	64.86
J.P.	8.83	0.85	0.00	1.01	7.06	21.01	28.25	5.05	1.77	73.83
R.G.	13.24	1.58	9.01	3.15	25.22	12.68	0.00	0.00	1.58	66.46
J.T.	5.51	1.73	31.73	7.05	16.45	4.46	11.75	8.22	2.88	89.78
Mean										77.56
L1: Spanish										
J.J.R.	6.33	2.85	9.05	2.72	0.00	6.33	0.00	1.45	5.07	33.80
F.J.G.	1.54	0.62	6.61	11.01	0.00	0.00	0.00	3.70	0.62	24.10
J.C.	4.00	4.67	14.28	6.67	0.00	9.33	4.67	1.33	4.00	48.95
O.N.	2.24	0.00	11.54	7.69	0.00	19.23	7.18	6.41	0.90	55.19
J.C.	10.71	0.00	18.37	6.12	0.00	0.82	10.20	0.00	7.14	53.36
S.E.	5.05	0.00	9.61	0.48	0.00	0.60	0.00	0.00	0.67	16.41
Mean										38.63

**TABLE IB. Total everyday usage of Spanish language, by daily activity**

Subject	TV	Radio	Teacher	Classmates	Family	Friends	Fiancée	Hobby	Reading	Exposure to Catalan
L1: Catalan										
X.S.	0.00	0.00	5.00	2.15	0.00	0.00	0.00	0.00	0.00	7.15
B.P.	3.18	0.00	14.13	3.80	0.00	5.52	0.00	3.10	5.41	35.14
J.P.	10.33	0.00	4.16	2.17	0.00	5.71	0.00	0.00	3.80	26.17
R.G.	7.24	0.00	6.01	6.11	0.00	12.08	0.00	0.00	2.10	33.54
J.T.	1.20	0.00	3.10	2.40	0.00	0.42	0.00	0.00	3.10	10.22
Mean										22.44
L1: Spanish										
J.J.R.	6.33	6.65	13.57	4.08	10.80	6.33	8.67	2.17	7.60	66.20
F.J.G.	5.67	2.89	1.10	11.01	19.97	11.01	13.46	5.21	5.58	75.90
J.C.	2.66	1.30	3.59	2.66	26.13	7.38	0.00	1.33	6.00	51.05
O.N.	2.24	0.00	6.92	6.92	8.78	12.82	0.00	5.02	2.11	44.81
J.C.	15.20	0.00	5.52	6.12	12.02	0.35	3.37	1.30	2.76	46.64
S.E.	5.05	0.00	12.61	4.48	33.80	3.80	18.70	5.08	0.07	83.59
Mean										61.37

Values are expressed as the percent of time (daily) each subject was aware of the Catalan or Spanish language in their regular daily activities. Values were obtained from a detailed questionnaire, which asked each participant to estimate time of exposure to language (hr/day) for several common activities.

v. 4.2 (MathWorks, Natick, MA) using Statistical Parametric Mapping software (SPM-99; Wellcome Department of Cognitive Neurology, London, UK). The fMRI scans were realigned to account for any movement during the experiment and then stereotactically normalized into the standard stereotactic space implemented in SPM-99 (Montreal Neurological Institute), to allow inter-subject data averaging and comparisons across tasks. Stereotactic normalization was first performed for the spin-echo high-resolution structural MRI volume, which was in the same space as the

functional activation volumes. The normalization parameters identified for this structural volume were then applied to the functional images by SPM-99. At this stage, the data matrix was interpolated to produce voxels of dimensions  $2 \times 2 \times 4$  mm. After stereotactic normalization, the common stereotactic space covered by our data involved complete planes from  $-20$  to  $+60$  from the bicommissural plane. The stereotactically normalized scans were smoothed through a Gaussian filter of  $10 \times 10 \times 10$  mm to reduce residual anatomical discrepancies between subjects, and im-

prove signal to noise ratio. Global differences in fMRI signal were co-varied out for all voxels. High-pass filtering was used to remove artefactual contribution to fMRI signal such as, for example, physiological noise from cardiac and respiratory cycles.

### Experimental paradigm

Blood oxygenation level measurements were collected in one single frame of 240 consecutive, T2\*-weighted fMRI multislice scans, during which the phonemic verbal fluency task was alternated for 12 times to a rest condition, where subjects were instructed to empty the mind and to avoid inner speech. Each epoch (12 verbal fluency epochs and 12 rest epochs) lasted 30 sec. In the phonemic verbal fluency task, a letter was called out loud to the subject immediately before the first scan. Subjects were requested to generate words covertly, without articulation, as many words as possible that began with that letter over the course of 30 sec but to move on to the next letter in the alphabet as soon as they were struggling to produce examples in order to maintain a high rate of production. They were asked to recall the words they had generated after the experiment, and the examiner recorded these. Half of the subjects generated words in Spanish during the first six verbal fluency epochs and in Catalan during the last six verbal fluency epochs, according to the following block design:

R-Span-R-Span-R-Span-R-Span-R-Span-R-Span-  
R-Cat-R-Cat-R-Cat-R-Cat-R-Cat-R-Cat-R-Cat  
(with R = rest, Span = Spanish, Cat = Catalan).

The other subjects performed the fluency task beginning with Catalan and ending with Spanish

R-Cat-R-Cat-R-Cat-R-Cat-R-Cat-R-Cat-R-Cat-R-Span-  
R-Span-R-Span-R-Span-R-Span-R-Span-R-Span.

This was done in order to neutralize potential confounds of language. The task sequence was randomized across subjects.

### Statistical comparisons

The present experiment is based on a classic block-subtraction method, grouping together the conditions concerning each language, Catalan and Spanish. Thus, the experiment was treated as a block design (fluency for a given language and rest). To emphasize the

commonalties and differences among the activation patterns of the subjects, statistical analyses were performed on a group basis according to the implementation of the general linear model for fMRI data devised by Friston et al. (1995). Random effect analysis as implemented in SPM99 was applied to the statistical analysis.

In order to assess brain activity attributed to general phonological word retrieval processes, not specifically associated to one language, the *main effect* of phonemic fluencies as opposed to the baseline conditions (rest condition) was first calculated within the entire group of subjects (Catalan + Spanish vs. Rest in all subjects).

Functional differences between the two languages were computed by *direct comparisons* between languages (i.e., L1–L2 and vice versa) for each group of bilinguals. By doing so, four different contrasts resulted: two investigating the effect of L1 as opposed to L2 (Catalan vs. Spanish in the Catalan group, and Spanish vs. Catalan in the Spaniard group) and two exploring the effects of L2 as opposed to L1 (respectively, Spanish vs. Catalan in Catalans, and Catalan vs. Spanish in Spaniards).

In addition, in order to evaluate the functional effect of the reduced exposure to the Spanish language in the Catalan group, the *interaction effect* was assessed. In this specific contrast, Catalans when generating words in Spanish were compared to Spaniards when generating words in Catalan:

(Spanish–rest) in Catalans (Catalan–rest) in Spaniards

Comparisons of means were made for all voxels by using the *t* statistics, thus generating statistical parametric maps of the *t* values SPM {*t*}, which were transformed to *Z* distribution maps. A standard threshold of  $P < 0.001$ , corrected, was adopted for the main effect of word retrieval vs. baseline. Direct contrasts among different languages were masked on the voxels identified by the main effect (thresholded at  $P < 0.001$ ) and threshold at  $P < 0.001$ . The interaction effects were calculated at  $P < 0.01$  and masked with the main effect threshold at  $P < 0.001$ .

## RESULTS

### Behavioral data

Eleven subjects were selected who fulfilled our criteria. All of them acquired either Spanish (six subjects) or Catalan (five subjects) as first language up to 3 years of life. After the age of 3 years they became

exposed to the second language, and consequently, they can be considered as early acquisition bilinguals (Fabbro, 1999). Since then, living in Barcelona, they used both languages in everyday life (all of them currently attended university classes where, in average, half of the courses are taught in Spanish and the other half in Catalan).

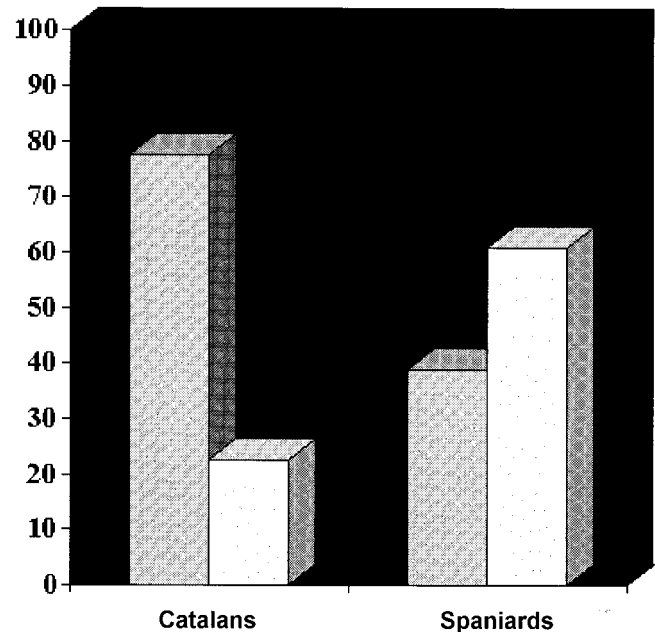
The degree of language proficiency was objectively assessed with a comprehension test as described in Perani et al. (1998). In more details, language proficiency of the participants was assessed with a word-translation task that included three lists of high-, medium-, and low-frequency words, respectively. Subjects had to translate from L2 to L1. Subject performance was compared using ANOVA (the group was a between-group factor and the word list type was a within-group factor). The ANOVA revealed no effect of word frequency and group. Proficiency was also measured with a story comprehension task in L1 and L2 through a questionnaire. ANOVA (one between-group factor and two within-group factors: language, replica) showed no group or language effects.

All 11 subjects had a high and comparable degree of language proficiency for both languages. Also, the number of words produced in the fluency task (as recalled after the scanning session) was comparable. Spaniards produced, on average, 32 words in Catalan and 30 words in Spanish; Catalans produced, on average, 37 words in Catalan and 34 words in Spanish. No difference was significant.

The group differs as the amount of daily language usage and exposure, either Catalan or Spanish being more prevalent in the everyday life, as was demonstrated by the detailed interview/questionnaire. In the six Spanish-born and in the five Catalan-born early bilinguals, the extensive investigation regarding the environmental exposure and usage to the two languages yielded the results shown in Table I and Figure 1. Catalans and Spaniards are mostly exposed to their first language (77.56% Catalan language in Catalans and 61.37% Spanish language in Spaniards,  $\chi^2 = 6.36$ ,  $P = 0.0117$ ) than to the second one. It is noteworthy that Catalans reported less exposure for their second language than did Spaniards (22.45 vs. 38.63%,  $\chi^2 = 5.21$ ,  $P = 0.0224$ ).

### fMRI results

The main effect of languages shows the brain activity associated to word retrieval in response to phonological cues. The overall pattern of activity associated to the verbal fluency tasks, relative to the baseline, is reported in Table II and Figure 2. The most consistent



**Figure 1.**

Differential exposure to languages as calculated in percent of daily time according to a detailed questionnaire (see Table I and text for details). Catalan subjects are relatively less exposed to their second languages in comparison to Spaniards. Gray columns, Catalan; white columns, Spanish.

focus of brain activity involved the left lateral prefrontal cortex, and in particular, the inferior (BA 44 and 45) and the middle frontal gyrus (BA 46). Additional foci of brain activity in the left hemisphere were located in the premotor cortex (BA 6/8), the inferior parietal lobule (BA 40), the superior and middle temporal gyrus (BA 22 and 37), and the thalamus. Brain activations were also found in the right inferior frontal gyrus (BA 47) and right cerebellum.

The areas differentially activated by the two languages (Catalan and Spanish) for the two different groups of subjects (Catalans and Spaniards) identified by the direct comparisons, are reported in Table III and Figure 2. No significant brain activation for L1–L2 (L1-effect) was found at the chosen threshold. Conversely, the subtractions of L2–L1 (L2-effect) resulted in significant differences: in Catalans, when producing words in Spanish, there were significant activations in the left inferior (BA 44 and 47), left middle (BA 46/10) frontal gyrus, left premotor cortex (BA 6), and insula. In addition, brain activity was also observed in the left inferior parietal lobule (BA 40) and in the left caudate nucleus. The right inferior frontal gyrus (BA 47) was also activated. In Spaniards, the same contrast resulted in a less ex-

TABLE II. Main effect for both languages

	<i>x</i>	<i>y</i>	<i>z</i>	Z-value
L inferior frontal gyrus (BA 44)	-44	10	32	5.70
	-54	12	24	4.88
L inferior frontal gyrus (BA 45)	-36	36	4	5.50
	-30	24	4	5.45
	-42	28	0	5.06
L middle frontal gyrus (BA 46)	-36	36	20	4.62
L premotor cortex (BA 6/8)	-40	4	60	4.51
	-46	12	52	4.23
	-42	8	56	4.20
L pre-SMA	-2	8	56	4.16
	-2	20	44	3.22
L inferior parietal lobule (BA 40)	-42	-28	40	4.49
	-32	-36	44	4.53
	-32	-32	36	4.19
L superior temporal gyrus (BA 22)	-54	-34	16	3.46
L middle temporal gyrus (BA 37)	-48	-54	-8	4.87
L thalamus	-6	-10	8	4.23
R inferior frontal gyrus (BA 47)	46	24	-4	4.17
R cerebellum	6	-46	-16	3.91

In both groups of bilinguals, Spanish and Catalan fluency conditions were pooled and compared to the baseline condition. This contrast indicated brain activity attributed to general phonological word-retrieval processes not specifically associated with one language.

tended pattern of brain activity within the left frontal lobe: in the inferior (BA 45) and middle frontal gyrus (BA 46/10) and in the insula.

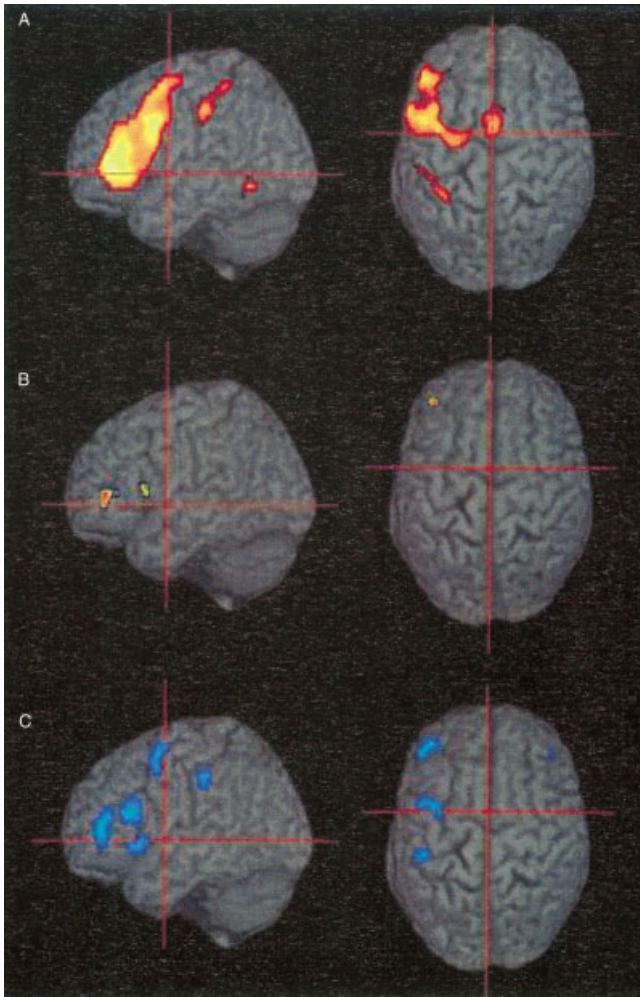
The interaction analysis showed significant brain activation foci in the left hemisphere, namely in the middle frontal gyrus (BA 46/10) and left inferior parietal lobule (BA 40). This difference may be considered to reflect the effect of lower exposure to the Spanish language in Catalans (Table IV).

## DISCUSSION

We examined the effects of age of acquisition and of exposure on the cerebral correlates of lexical search and retrieval in a population of early-acquisition, high-proficient bilinguals. We will first address how the age of L2 acquisition in early bilinguals is responsible for differences in cerebral activation patterns, and then, how usage/exposure may also be a crucial factor.

Our results underline that the age of language acquisition is a crucial factor, even in early bilinguals with a very high degree of proficiency for L1 and L2. Indeed, the direct comparisons between L1 vs. L2 in our groups showed no significant activation foci at the chosen threshold, while the reverse contrast (L2 – L1) resulted in significant differences in brain activity.

Classically, among researchers, the effects of age-of-onset of L2 acquisition were highly debated and the so-called “critical period” for language acquisition has been a constant source of controversy (Elman et al., 1997). The critical period hypothesis proposed by Lenneberg (1967), which considers puberty as the limit, relies on the main assumption that age-related effects reported in L2 studies are the results of maturational changes in brain structures, which are involved in acquiring a language. L2 learning after the critical period was postulated to be different in nature from pre-pubertal learning, because of the requirement for a more conscious, labored effort. Other psycholinguists argued against a native-like performance, even if L2 is learned before the end of the critical period (for review, see Harley and Wang, 1997). For instances, Hyltenstam (1992) showed that the onset for L2 acquisition after age 7 may lead to incompleteness not only in grammar but in the lexicon as well. Furthermore, in Johnson and Newport’s studies (1989, 1991) native-like performance was achieved only among bilinguals with age of L2 acquisition between 3 and 7 years, whereas Ioup (1989) found incomplete acquisition among immigrants who arrived between age 6 to 9 years in the United States. It becomes clear that it is difficult to set a specific age at which the critical period terminates, but most researchers converge by setting it



**Figure 2.**

Brain activity during phonological fluency task. **A:** Main effects of languages (L1 and L2) vs. baseline in the whole group of bilinguals. **B:** Direct comparison between L2 (Catalan) vs. L1 (Spanish) in Spaniards. **C:** Direct comparison between L2 (Spanish) vs. L1 (Catalan) in Catalans.

at age 6 to 7 years, hence, bilinguals who acquire their L2 before that age are called “early bilinguals” (Fabro, 1999).

Our behavioral results did not indicate crucial differences in language processing and language use when early bilinguals acquire L2 after age 3. Indeed, language processing, as revealed by the evaluation of proficiency in comprehension, was comparable among our subjects (furthermore, the fluency task performance, measured according to the number of words produced in L1 and L2, was comparable for both groups). However, the present data indicate that, at the macroscopic cerebral level, additional neural resources are involved when generating words in L2

at a comparable level of language performance to that of L1. A possible interpretation is that the generation of words, in the language acquired first in life, is less effortful, and is thus reflected, at the neural level, by the engagement of less extensive neural resources, even when proficiency is held constant. Because phonemic fluency is a relatively difficult, effortful task, the difference between L2 and L1 (in the L2 – L1 subtraction) may be attributed to the recruitment of additional resources within a dedicated network.

This interpretation must be reconciled with the limited findings derived from other imaging investigations of language production in early bilinguals (Chee et al., 1999a; Kim et al., 1997). Kim et al. (1997) studied early and late bilinguals. Of these, six had been exposed to L1 and L2 during infancy (the exact age of L2 acquisition however, was not provided) and six began learning L2 after puberty. The experimental task required covert extended language production (discourse). The authors found Broca’s area differentially activated for the two groups: overlapping activations for both languages in early learners, and spatially segregated activations in late learners. However, a major problem for the interpretation of these results is that no formal assessment of language proficiency was conducted. Since there is a general negative correlation between age of acquisition and proficiency (Johnson and Newport, 1989), these two variables are confounded in this experiment. Kim et al.’s conclusion was that age of acquisition is a major factor in the cortical organization of second language processing. The overlapping activations in Broca’s area for L1 and L2 in early bilinguals are in contrast with the differential activation for L1 and L2 in early bilinguals in our study. Several factors may account for this difference. The study by Kim and coworkers focused only on Broca’s area, whereas the activation differences between L2 and L1 in our study were not only found in Broca’s area but also extended to other regions in the lateral frontal cortex. In addition, task-related effects should be taken into consideration. The production of extended speech, as in Kim et al.’s study (1997), relies on a more “natural” elaboration of the linguistic material; in contrast, most of the linguistic processing evaluated in bilinguals is related to phonological tasks (Flege et al., 1999), or to morphosyntactic processing (Weber-Fox and Neville, 1996). The differences in brain activation between our study and Kim et al.’s study may thus reflect the task differences. In general, verbal fluency tasks are considered to assess the ability to access lexical items through a number of strategic search processes, which may involve the retrieval of phonological, lexical, and semantic knowledge (Tro-



**TABLE III. Direct comparison between languages**

	x	y	z	Z-value
L1 vs. L2				
Catalans: No voxels above threshold				
Spaniards: No voxels above threshold				
L2 vs. L1				
Catalans				
L insula	-28	16	8	4.15
	-32	14	0	3.73
L inferior frontal gyrus (BA 44)	-36	18	28	3.41
L middle frontal gyrus (BA 46/10)	-40	44	8	3.95
	-46	40	16	3.57
L inferior frontal gyrus (BA 47)	-32	18	-4	3.69
L caudate nucleus	-16	2	20	3.57
L premotor cortex (BA 6)	-40	4	60	3.71
	-48	4	52	3.40
L inferior parietal (BA 40)	-44	-28	44	3.46
R inferior frontal gyrus (BA 47)	48	20	-8	3.58
Spaniards				
L inferior frontal gyrus (BA 45)	-48	36	8	3.10
L middle frontal gyrus (BA 46/10)	-40	44	8	3.61
L insula	-34	16	12	3.51

Table demonstrates the L1 effect in Catalans (Catalan vs. Spanish) and Spaniards (Spanish vs. Catalan), and the L2 effect for Catalans (Spanish vs. Catalan) and Spaniards (Catalan vs. Spanish)

ster, 1998). The multi-component nature of this test makes it sensitive not only to frontal lobe damage (Milner, 1964), but also to schizophrenia (Spence et al, 2000) and dementia (Monsch et al., 1992).

Different considerations apply to Chee et al.'s study (1999a). Using fMRI in Mandarin-English bilinguals, they found no differences within the left prefrontal cortex when comparing a word stem completion task in early bilinguals and late bilinguals with high degree of language proficiency. A group of early bilinguals (L2 acquisition before age 6) were compared to late bilinguals (L2 acquisition after age 12). Subjects were studied when producing words cued by a word stem presented visually. The authors predicted that the processing of Mandarin would require neural resources distinct from English, since Mandarin has an ideographic writing system. However, the pattern of brain

activation in response to Mandarin was similar to that observed for English and, furthermore, this was true for both early and late bilinguals with high proficiency. A possible explanation for these findings may be found, again, in the nature of task: from a cognitive viewpoint, word stem completion in Chee et al.'s study, is a completely different task than word generation on phonological and semantic cueing.

While ideally suited for the investigation of priming effects, word-stem completion on the basis of written word stems relies extensively on orthographic knowledge, and may be less demanding in terms of linguistic requirements (Buckner et al., 1995, 2000). Moreover, age of L2 acquisition of Chee et al.'s subjects varied from age 2 to age 6, whereas our study includes only subjects who learned L2 at age 3, when admitted to kindergarten.

It is noteworthy that differences in age of acquisition were found in another class of tasks, involving access to morphosyntactic knowledge. Weber-Fox and Neville (1996) reported an ERP study of syntactic and lexical-conceptual violations in bilinguals where subjects were categorized by their age of first exposure to L2: at 1-3 years of age, 4-6 years, 7-10 years, 11-13 years or greater than 16 years. Later exposure to L2 was significantly associated with worse performance, at least for syntactic violations. Even the group of

**TABLE IV. Language exposure effects**

	x	y	z	Z-value
L middle frontal gyrus (BA 46/10)	-40	46	4	2.44
L inferior parietal lobule (BA 40)	-44	-28	40	2.64

The data refer to the interaction effect in Catalans generating words in Spanish, a language to which they are not intensively exposed, compared to Spaniards producing word in Catalan.

those exposed to L2 as young as 1–3 showed a different pattern to syntactic phrase structure violations. Combining these data with our results, one may conclude that even when a L2 is learned very early in life, different neural resources may act for its processing, which may not be necessarily be associated to a worse language performance at the behavioral level. These cerebral differences may be particularly sensitive to effortful language tasks, such as word generation on phonological cueing, or morphosyntactic tasks.

The present data show that a differential exposure to a given language may intervene on cerebral representations in multilinguals, even in the case when the degree of proficiency is kept constant. That differential exposure, reflected in a more intensive and frequent usage of a given language, may be a crucial factor has already been demonstrated in aphasiology. In particular, recovery studies have clearly indicated that one of the polyglot's languages may recover in a different manner from the others (Albert and Obler, 1978; Paradis, 1998). More than a century ago, Pitres (1895) described the influence of the language spoken in the patient's environment on preferential recovery, focusing on what has come to be known as Pitres's law. According to the latter, the language spoken most frequently and intensively before brain damage (which is not necessarily the language learnt earlier in life) is the one to recover first. The more extensive brain activity observed in the left lateral frontal cortex for Catalans, when generating words in Spanish, the second language with lower usage for this group, in comparison with the more limited activation found in the Spaniards for word finding in Catalan (Fig. 2), may reflect this environmental factor. Indeed, the interaction effect confirms this hypothesis: the brain activity associated with fluency in L2 selectively the left lateral frontal and parietal cortex for the Catalans than for the Spaniards. Catalans in Catalonia, albeit highly proficient in Spanish since early childhood, are less exposed to Spanish than Spaniards living in Catalonia to their L2 (Catalan).

A previous fMRI experiment based on phonemic fluency in multilinguals (Yetkin et al., 1996), showed larger foci of brain activity for the "less fluent" languages. The experimental group was composed of six heterogeneous subjects, fluent in at least two languages and non-fluent in a third language. "Fluent" was empirically defined as speaking the language currently and for at least 5 years, whereas "non-fluent" was used for languages studied for 2 to 4 years and without regular use in the everyday life. Moreover, English was always labeled as L1, despite the fact that the native language was not English in two of the six

subjects. While the resulting findings are difficult to interpret given the lack of control of important variables such as the age of language acquisition and level of proficiency, they seem to be in agreement with the "exposure" hypothesis.

The present findings indicate that activity in the left frontal cortex during verbal fluency in bilinguals is less extensive in the case of the language acquired first, which is associated with more extensive usage/exposure. Many functional neuroimaging studies have implicated the left frontal convexity in language processing tasks. For instance, increased blood flow was observed specifically during semantic monitoring (Démonet et al., 1992), word generation (Martin et al., 1996; Petersen et al., 1988), semantic and phonemic fluency (Frith et al., 1991; Mummery et al., 1996; Paulesu et al., 1997), and with verbal working memory tasks (Smith et al., 1996). More recently, studying word generation tasks of increasing task difficulty, Thompson-Schill and colleagues (1997, 1999) suggested that brain activity in these areas, that is, Brodmann areas 45, 46, and 47 in the left inferior and middle frontal gyrus, is presumably associated with the general selection processes of information among competing alternatives from semantic memory. These researchers underscored that these cortical areas would be differentially engaged on the basis of task difficulty. When the word-to-be-generated possesses more competing alternatives, among which the subject has to select, a larger left prefrontal network was involved. With increasing task difficulty, more neural activity should thereafter be evoked. Likewise, the effect of experience on task performance resulted in decreased neural activity (Thompson-Schill et al., 1999). A substantial body of information, particularly from the past 10–15 years of research, has demonstrated that neuronal properties in auditory, sensory, visual, and motor cortices can be reorganized in the adult human brain, either in response to lesions or to experience alone. Representations in a particular brain area are said to contract (or expand) so that they can occupy a smaller (or larger) plot of neural "real estate," an effect termed "representational plasticity" (Donoghue, 1995). Practice-related changes in a word-generation task have been observed in a study where the prefrontal brain areas were less active in the well-practiced automatic condition (Raichle et al., 1994). Later, Petersen et al. (1998) further investigated the effects of practice on a verbal task using PET. The observed reduced brain activity in the left frontal lobe following practice was putatively related to processing differences between high and low practice performance in verb generation. That experience alone may

decrease brain activity in the left prefrontal cortex was highlighted by a recent PET study (Petersson et al., 1999) during the recall of abstract designs. Specifically, practice-related decreases were observed in the left lateral frontal cortex (BA 9, 10, and 46).

It may be hypothesized that similar changes, which we interpret to reflect long-term cognitive plasticity, were responsible for the effects of age of acquisition and of exposure in our study. As a task becomes more automatic, performance will gradually rely less on prefrontal support, and decreases in left prefrontal activity might reflect a decreasing dependence on controlled processing. Here, we particularly stress that practice, in the case of bilingual language processing, is not directly equivalent to proficiency (in terms of absolute level of fluency), but rather to the more intensive use/exposure of a language. Intensive exposure to a language in a bilingual environment will lead to a lower activation threshold (Green, 1986) and therefore to a higher degree of automaticity, i.e., decreased dependence on controlled and attentional processing. Supposedly, this would be reflected in decreased activity of the prefrontal region. We suggest that some components of the neural network subserving word generation have a dynamic role, and this will be reflected in functional reorganization of the language-processing network during intensive exposure.

Our findings are also compatible with the framework proposed by Green (1986). Green's model of language control presupposes the existence of reciprocally inter-dependent language subsystems for the selection process among multiple languages in bilinguals. Language selection is regulated by a device (the so-called "language-specifier") that prevents code mixing. This stage is followed by the operation of a resource generator, which, following the specification of the language, activates the appropriate language output system. In short, if the polyglot intends to speak in L1, the language specifier selects the intended language. Then, the resource generator activates the subsystems for word output in L1 and at the same time suppresses the word output subsystem for L2 and vice versa, in order to avoid code mixing. In terms of energy resources, the model suggests that language selection should be performed with less effort in the case of the more available language. This is a concept adapted by many clinical researchers in order to explain specific recovery patterns in polyglot aphasia (Aglioti and Fabbro, 1993; Aglioti et al., 1996; Abutalebi et al., 2000). For instance, it has been claimed that one of the languages may selectively recover because of a lower activation threshold, which is strongly linked to language exposure (Fabbro, 1999).

This is the first anatomo-functional evidence that both age of acquisition and amount of exposure to a language may affect the extent of activation during a lexical search and retrieval task. The finding of less extensive activity in the left prefrontal cortex is consistent with the selection and use of a more available and "automatic" language. Repeated activation of the cortical representations in a language may be expected to strengthen the neocortical connections in such a way that the neural network could support lexical retrieval with a less extensive engagement of prefrontal regions.

## CONCLUSION

Functional neuroimaging with PET and fMRI offers us a direct window into the complex mechanism of interaction among language systems in the human brain, and thus appears to be a valuable tool to attempt to delineate the general principles of cerebral language organization in bilinguals. In broad outlines, we underline the fact that the bilingual brain cannot be viewed as the sum of two monolingual language systems, but rather considered as a unique and complex neural system which may differ in individual cases. There are several variables that may be responsible for the above-mentioned differences; among them the prominent role of degree of proficiency was underlined by neuroimaging studies carried out in the last years. In the present investigation in early high proficient bilinguals, we addressed the issues of age of second language acquisition and level of language usage/exposure. We found differences in brain activation patterns for a word generation task. These differences appear to be associated with these two variables never specifically addressed in past imaging studies. Interestingly, these variables appear to affect the macroscopic neural level during lexical retrieval: in the case of word generation more extensive cerebral activations are associated with the language acquired as second even if mastered with equal level of proficiency. This effect appears to be modulated by exposure, as it is less evident in bilinguals who are more extensively exposed (in percentage) to the second language. The knowledge about how language is organized in the human brain and the possible variations associated with multiple languages and crucial functional variables may have important implications for all contexts in which multi-lingual interactions are at play. For example, the finding that language exposure is a crucial factor for the neural representation of multiple languages may provide important inputs to the educational field, such as in the case of second

language teaching. Our findings also suggest that the best approach to language-impaired bilinguals may be based on the language to which the subject was more intensively exposed pre-morbidly.

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