Brain (1998), **121,** 1841–1852

The bilingual brain

Proficiency and age of acquisition of the second language

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Summary

Functional imaging methods show differences in the pattern of cerebral activation associated with the subject's native language (L1) compared with a second language (L2). In a recent PET investigation on bilingualism we showed that auditory processing of stories in L1 (Italian) engages the temporal lobes and temporoparietal cortex more extensively than L2 (English). However, in that study the Italian subjects learned L2 late and attained a fair, but not an excellent command of this language (low proficiency, late acquisition bilinguals). Thus, the different patterns of activation could be ascribed either to age of acquisition or to proficiency level. In the current study we use a similar paradigm to evaluate the effect of early and late acquisition of L2 in highly proficient bilinguals. We studied a group of Italian–English bilinguals who acquired L2 after the age of 10 years (high proficiency, late acquisition bilinguals) and a group of Spanish–Catalan bilinguals who acquired L2 before the age of 4 years (high proficiency, early acquisition bilinguals). The differing cortical responses we had observed when low proficiency volunteers listened to stories in L1 and L2 were not found in either of the high proficiency groups in this study. Several brain areas, similar to those observed for L1 in low proficiency bilinguals, were activated by L2. These findings suggest that, at least for pairs of L1 and L2 languages that are fairly close, attained proficiency is more important than age of acquisition as a determinant of the cortical representation of L2.

Keywords: bilingualism; proficiency; language comprehension; PET

Abbreviations: ANOVA = analysis of variance; fMRI = functional MRI; HPEA = high-proficiency early acquisition bilinguals; HPLA = high proficiency late acquisition bilinguals; L1 = first language; L2 = second language; LPLA = low proficiency late acquisition bilinguals; rCBF = regional cerebral blood flow; SPM = statistical parametric map

Introduction

Psycholinguists and neurolinguists have focused their investigations with bilinguals on the use, acquisition and eventual loss of the first language (L1). However, studies of second language (L2) acquisition and use are gaining importance. Several theoretical issues, in areas such as language acquisition, cortical plasticity and performance theory, might be advanced by an increased understanding of the ways in which multiple languages are represented in the bilingual speakers' brain/mind.

In the psycholinguistic field, the study of L1 acquisition has given rise to a large number of models. The parameter setting approach, in conjunction with a classical statistical learning module, has become the leading model for many investigators (Chomsky and Lasnik, 1993; Pinker, 1994). Linguistic parameters, i.e. sets of possible grammatical variations (values) within a frame of invariant principles, are considered to be part of the innate endowment of universal grammar; exposure to a specific linguistic environment results in the fixation of one of the possible values of each parameter. Within such an approach one may very well ask what happens when the acquisition of L1 requires the fixation of a parameter at one value, while the acquisition of L2 requires a different value for the same parameter. A classic example of parametric variation is given by the different direction in which a noun can be recursively modified by other words. For example, the English phrase 'monthly^4 sales^3 department^2 head^1' is translated into Italian as 'capo^1 settore^2 vendite^3 rateali^4' where successive modifications of the noun head/capo are indicated by the progressive numeration. To learn both Italian and English, one would have to fixate the direction parameter in two opposite ways: the English phrase expands to the left, whereas the Italian expands to the right. Will this give rise to greater trouble than if both languages had the same value for this parameter? Will the learner first fixate a parameter and then use that value to try and process L2 or will a different value be used for L2? These are important questions that one needs to answer to gain a deeper understanding of the language faculty (Epstein *et al*., 1966).

Relating this line of research to the neural substrate used to represent the knowledge of L1, and eventually of L2, is also an essential aspect of this quest. Investigators such as Chomsky, Katz and Fodor (for a review, see Pinker, 1994) consider language as a characteristic faculty of humans, much as navigation by sonar is for bats and orientation by polarized light is for bees. Studies in neuropsychology, an empirical discipline which tries to link cortical structures to functions, have demonstrated that language processing is mediated by a dedicated cortical network, located in the perisylvian areas of the left hemisphere of most speakers. This finding, as well as other observations, has been used to argue that humans can acquire language because a 'language organ' has emerged in cortical structures of our left hemisphere (Chomsky, 1975). Whether L2 acquisition is consistently associated with a cerebral substrate comparable to L1 is still a matter of debate. Some investigators have reached the conclusion that different cerebral networks support L1 and L2 acquisition. Occasionally, after a brain lesion, a polyglot becomes aphasic in only one of the languages originally mastered (Albert and Obler, 1978; Paradis, 1995). This dissociation, together with some evidence from electrical cortical stimulation (Ojemann, 1983), suggests that the brain areas recruited for learning and processing the L1 are different from those recruited for L2. Brain imaging of bilingual subjects has helped us to reveal differences between the representation of L1 and L2 (Klein *et al*., 1995; Perani *et al*., 1996; Weber-Fox and Neville, 1996; Yetkin *et al*., 1996; Kim *et al*., 1997; Dehaene *et al*., 1997). Neuropsychological and imaging studies, however, have failed to pinpoint a consistent neuronal substrate for L2. The languages that were involved in the different studies were quite disparate. Likewise, the tasks that were used were also different, and the patients or subjects tested spoke L2 with different abilities. All these factors may have prevented the emergence of a consistent pattern of results.

A factor that may affect the cortical representation of language is the moment in life when language is acquired. There is evidence that when L1 is learned with a delay it is impoverished (Mayberry, 1993). Other data supporting the notion of the existence of a critical period (Lenneberg, 1967) derives from the observed difficulty in learning L2 after puberty. Children learn languages with greater ease than adults (Johnson and Newport, 1989; Flege *et al*., 1995; Weber-Fox and Neville, 1996). The phonological and morphological components seem particularly deficient when L2 is learned after puberty. In contrast, the lexicon seems to be acquired with greater ease.

However, the notion of a critical period for the acquisition of L1 has been recently challenged. For instance, Vargha-Khadem *et al.* (1997) report that a patient suffering from Sturge–Weber syndrome affecting the left hemisphere, who had failed to acquire language, made excellent linguistic progress after his left hemisphere was surgically removed at the age of 9 years. They argue that after surgery the right hemisphere took over functions normally mediated by the left hemisphere, including language acquisition. Even if this claim is in need of confirmation by a detailed follow-up study, it invites us to be prudent when making claims about the impossibility of learning L1 late.

In a previous PET investigation (Perani *et al*., 1996) bilingual Italian subjects with a moderate command of English were studied while they were listening to stories in English and Italian. A large network of left hemispheric areas, including perisylvian regions and the temporal poles, was activated when volunteers listened to the Italian stories. When they listened to the English stories, a more reduced symmetrical network within the superior and middle temporal gyri was activated. Using functional MRI (fMRI), it has been shown that, while L1 is mediated by a similar brain network in all volunteers, the network that mediates L2 varies greatly from subject to subject (Dehaene *et al*., 1997). In both the Perani *et al*. (1996) and Dehaene *et al*. (1997) studies, the volunteers had mastered L2 to a moderate level of competence (low proficiency). Thus, the different pattern of activation could be ascribed either to age of acquisition, or to proficiency level.

In this paper, we focus on the effect of age of acquisition on the neuronal substrate of L2. By comparing the results of this study with the results of the previous investigations, we may be able to evaluate the role of proficiency *per se*. We report two studies with subjects who have learned L2 to a high degree of proficiency, but who differ in the age of acquisition of the second language. In the first study we investigated nine adult male Italian subjects who learned English after the age of 10 years, but who, nevertheless, achieved excellent English speaking skills (the HPLA—high proficiency, late acquisition—group). In the second study we investigated 12 Spanish-born subjects who learned Spanish and Catalan very early in life and spoke both languages for most of their lives (the HPEA—high proficiency, early acquisition—group). In both studies we explored the cortical activation while volunteers listened to stories in L1 and L2. The data were compared with the results reported by Perani *et al*. (1996) on low proficiency, late acquisition (LPLA) subjects.

Methods

Subjects

Experiment 1

Nine right-handed male native speakers of Italian were tested. Their age ranged from 19 to 50 years. All volunteers had

Italian parents and had lived most of their life in Italy. They learned English at school after the age of 10 years. All volunteers spent >1 year in an English-speaking country (range 1–6 years) and they spoke and/or read both languages in their daily activities. Four subjects were scientists from the San Raffaele Scientific Institute, one subject was an undergraduate student, three subjects were postgraduate students at a School for Interpreting (Civica Scuola Superiore per Interpreti e Traduttori del Comune di Milano), and one subject was a teacher of Italian linguistics at the same school. In this study, the pattern of cerebral activation in these HPLA subjects is compared with that of the volunteers studied by Perani *et al*. (1996). That group included nine right-handed male native speakers of Italian, aged between 21 and 32 years. They were university students who had learned English at school. None of the latter volunteers had been exposed to English before the age of 10 years, nor had they ever stayed for >1 month in an English speaking environment. These LPLA volunteers had mastered English to a moderate level of proficiency.

Language proficiency of the participants in this study and in that of Perani *et al*. (1996) was assessed with a word-translation task that included three lists; the first list had only high-frequency words, the second list medium-frequency words and the third list low-frequency words. The subjects had to translate from L2 to L1. The performance of the HPLA volunteers was compared with that of the LPLA volunteers from the study of Perani *et al*. (1996). Performance was compared with an analysis of variance (ANOVA) (the group was a between-group factor and the word list type was a within-group factor). The ANOVA revealed a main effect of word frequency [$F(2) = 199$, $P < 0.00001$]; irrespective of group, performance on low-frequency words was significantly poorer than performance for intermediate and high-frequency words, while no significant difference emerged between intermediate and high-frequency words (Sheffé F test, $P < 0.05$). The ANOVA also showed that the HPLA subjects performed significantly better than the LPLA subjects; [$F(1,16) = 81$, $P < 0.0001$]. This group effect was further qualified by a group × list interaction [$F(2,32) = 21$, $P < 0.00001$]. *Post hoc* analyses, carried out with simple main effects, revealed reliable group differences for the intermediate and low frequency lists ($P < 0.0001$) while performance on the high-frequency word list was virtually identical in both groups (see Fig. 1A).

Proficiency on story comprehension was assessed during the PET experiment through five questions that were asked following each scan. ANOVA (one between-group factor and two within-group factors: language and replications) showed a significant between-group effect [$F(1,16) = 19$, $P < 0.0005$] and a significant language effect [$F(1) = 5.8$, $P = 0.03$]. These were qualified by a significant group × language interaction [$F(1,16) = 7$, $P < 0.02$]. *Post hoc* analyses with simple main effects also revealed that there was no between-group difference for Italian stories [$F(1,33) = 1$, not significant] and that there was a significant difference between the groups for English [$F(1,33) = 24$, $P < 0.001$] (see Fig. 1B). In addition, the HPLA performance in the two languages was identical.

Experiment 2

The effect of age of acquisition was studied using a population of ‘early’ bilinguals with high proficiency in Spanish and Catalan. The decision to use a different pair of languages was due to practical reasons as identification of true ‘early’ bilinguals for Italian and English proved to be very difficult. Spanish and Catalan are more ‘similar’ than Italian and English, both being Romance languages. In the first place, Romance languages have a high degree of lexical overlap (in the order of 40% for all major variants). Furthermore, they are similar at the phonological level, both from the point of view of the number of vowels and of the role of syllabic structure in rhythm assignment. In contrast with Germanic languages, such as English, the Romance languages are highly inflected, with a rich morphology. At the syntactic level, they share common features, such as flexibility in the position of the subject, and the possibility of dropping the pronominal subject (Comrie, 1987).

A group of 12 Spanish–Catalan early bilinguals participated in the HPEA study. They were selected from a pool of >80 subjects who were selected through behavioural tests and directed interviews. These tests were designed to choose the most proficient bilinguals who fulfilled a series of criteria. They had to speak both languages equally well, and to have spoken both languages well since childhood. However, their family spoke only in Spanish, or only in Catalan, at home. The 12 subjects that were selected were right-handed male adults aged between 19 and 27 years. Half of the subjects were exposed exclusively to Spanish (Spanish dominant volunteers) and the other half to Catalan (Catalan dominant volunteers) during the first 2 years of life. One cannot rule out occasional exposure to the other language, although if such exposure took place it was of limited extent.

The performance of these HPEA subjects on the behavioural tests, like the one described above for the HPLA group, was evaluated by an ANOVA (dominance as a between-group factor and word list as a within-group factor). There was no significant difference between the groups. In addition, comprehension of the stories presented during the PET scan, as assessed by means of five questions, uncovered no group or language differences (see Fig. 1C and D).

All these studies were performed on volunteers after they had signed an informed consent form. All subjects were tested according to the guidelines for human research developed by ethical committees of the participant institutions and conforming to the Helsinki Declaration.

Experimental conditions

Experiment 1

The paradigm was like the one used by Perani *et al*. (1996). Two regional cerebral blood flow (rCBF) measures were

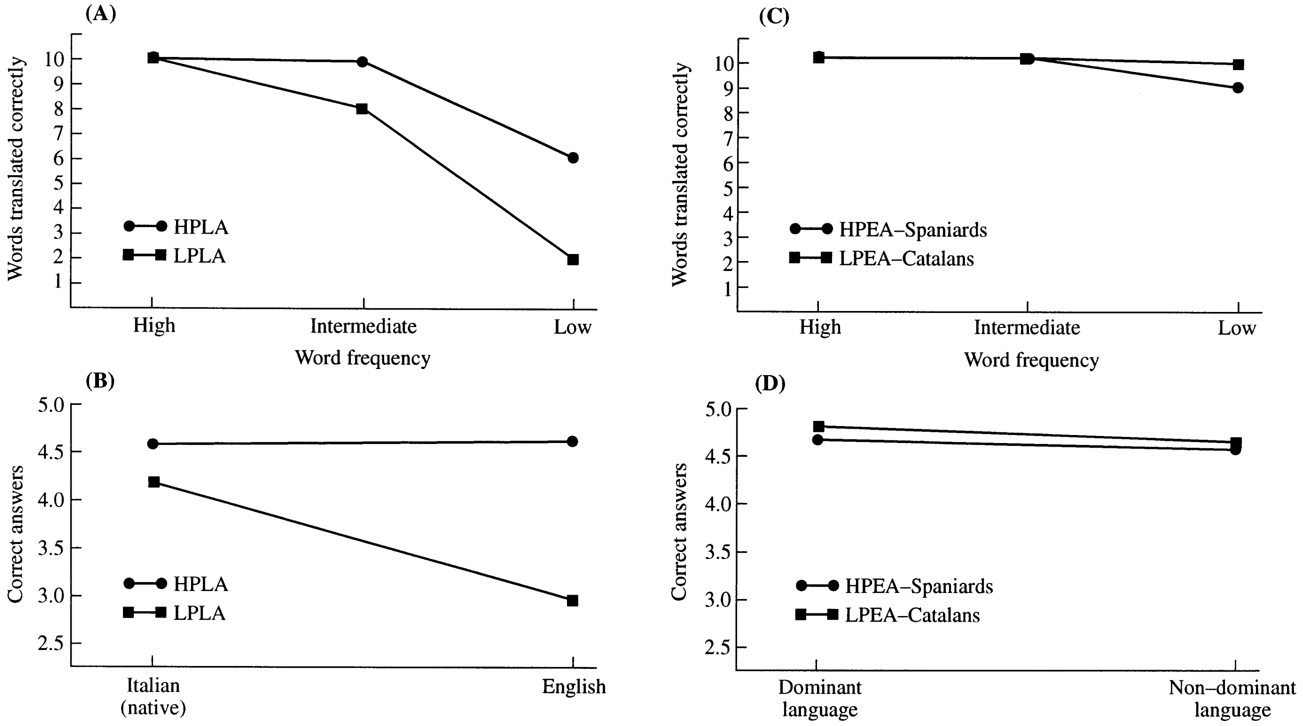

Fig. 1 Proficiency level for L1 and L2 in LPLA, HPLA and HPEA subjects. Proficiency was measured with a word-translation task for lists of high-frequency, intermediate and low-frequency words (**A** and **C**) and with story comprehension questionnaires after PET scans (**B** and **D**).

taken on the HPLA English–Italian bilinguals while they were listening to (i) a story in Italian, (ii) a story in English and (iii) a story in Japanese, an unfamiliar language. Two baseline conditions were used, i.e. listening to (i) backwards Japanese and (ii) attentive silence. Different short stories were used for each scan. There were four stories in Italian and four stories in English. Half of the subjects listened to two stories in Italian (I1 and I2) and to two stories in English (E3 and E4) and the other subjects heard the same stories but with the languages switched, i.e. I3, I4, E1 and E2. This was done to neutralize potential confounds of language and meaning. The task sequence was randomized across subjects. Subjects were instructed to listen carefully to the stories and warned that at the end of each scan they would be asked questions about their content.

Experiment 2

The 12 volunteers in this experiment were Spanish–Catalan bilinguals. They were selected in Barcelona, Spain, and a date was arranged to fly them to Milan where the PET scan study was conducted. Each bilingual volunteer had four rCBF measurements taken while they were listening to (i) a story in the dominant language, i.e. L1 (Catalan in half of the subjects and Spanish in the other half), (ii) a story in the non-dominant language, L2 and (iii) Spanish and Catalan stories played backwards. Thus, a total of 12 rCBF measurements per volunteer were made. Only one control condition was used in this experiment because, in previous experiments (Perani *et al.*, 1996; Dehaene *et al.*, 1997), the backward speech condition had proved to be adequately informative. Backward speech is physically quite similar to speech yet it is not speech, and it does not constitute a signal that can be produced by the human vocal tract.

PET procedures

rCBF was measured by recording the distribution of radioactivity following the intravenous injection of [^{15}O]-labelled water ($H_2{}^{15}O$) with the GE-Advance scanner (General Electric Medical System, Milwaukee, Wis., USA) which has a field of view of 15.2 cm, allowing sampling of the entire brain, including the cerebellum, all at once. Data was acquired by scanning in 3D mode. A 5-mCi bolus of $H_2{}^{15}O$ was injected as a tracer of blood flow and 90-s scans were acquired immediately after the initial rise of discharges (Mazziotta *et al.*, 1985; Fox and Mintun, 1989). After attenuation correction (measured by a transmission scan), the data were reconstructed as 35 transaxial planes by 3D filtered back projection algorithm using a Hanning filter (cut-off 4 mm filter width) in the transaxial plane, and a Ramp filter (cut-off 8.5 mm) in the axial direction. The integrated counts accumulated over 90-s scans were used as an index of rCBF (Mazziotta *et al.*, 1985; Fox and Mintun, 1989)

PET data were analysed using Statistical Parametric Mapping (SPM95, Wellcome Department of Cognitive Neurology, London, UK) (Friston *et al.*, 1995*a*). The original brain images were first realigned and then transformed into a standard stereotactic anatomical space (Friston *et al.*, 1995*b*). Stereotactically normalized images were also smoothed with a Gaussian filter (16 × 16 × 16 mm). Statistical analyses were performed according to the SPM95 implementation of the general linear model (Friston *et al.*, 1995*a*). Global differences in CBF were carried out and comparisons by means across conditions were calculated using the t statistic (Friston *et al.*, 1990; Friston *et al.*, 1995*a*). The resulting set of t-values constituted a statistical parametric map (SPM$\{t\}$) which were transformed into Z-score maps (SPM$\{Z\}$). Only regional activations significant at $P < 0.001$ (uncorrected) were considered.

Differences of activation patterns between the HPLA and the LPLA English–Italian bilinguals were characterized formally as a group × task interaction using the appropriate linear contrasts. The group × task interaction effects were computed using both the attentive silence and the backward speech as baselines: HPLA (English – Silence) – LPLA (English – Silence); HPLA (English – Backward) – LPLA (English – Backward). Using two baseline tasks for these comparisons reduces the possibility that the difference of activation between the two groups is due to a rCBF reduction in one baseline task for the HPLA volunteers only

For the interaction effects, a less harsh threshold ($P < 0.01$) was applied to the statistical maps. We also report the between-group differences at $P < 0.05$. These should be considered only as indicating possible trends.

Results

The results of Experiment 1 showed that listening to Italian stories (L1) compared with backward language yielded a similar pattern of activation in HPLA volunteers which was similar to that observed in the LPLA bilinguals (Perani *et al.*, 1996). Activation foci were found in the left hemisphere in the temporal pole, the superior temporal sulcus, middle temporal gyrus and hippocampal structures. Listening to English stories (L2) compared with backward language showed a similar activation pattern in the left hemisphere to the one observed for the Italian stories (L1) in the HPLA group. We found activation foci in the left temporal pole, middle and posterior temporal gyri and, bilaterally, in the hippocampal structures (see Table 1). These results contrast with those for the LPLA bilinguals who showed no activation for L2 in the temporal poles, or in the left anterior and posterior part of the middle temporal gyrus.

The group × task interaction effects, using either attentive silence or backward speech as the baseline, showed significantly greater activation in the HPLA bilinguals in the temporal poles bilaterally, in the left superior temporal sulcus and in the right lingual gyrus. The middle temporal gyrus was also activated bilaterally (see Table 1 and Fig. 2).

The direct comparisons of activation while HPLA bilinguals were listening to Italian and English stories (Italian – English) and vice versa did not show any significant activation foci.

In Experiment 2, with the HPEA bilinguals, the activations observed when the volunteers were listening to the stories in L1 or L2 were assessed as main effects in comparison with backward language (see Table 2). The pattern of results was similar to that reported above for the HPLA volunteers. For both languages we observed bilateral foci of activation in the temporal poles, hippocampal structures and lingual gyrus, and, on the left side, in the superior temporal sulcus, the inferior parietal lobule, the lingual/cuneus region and in the cerebellar vermis.

There were, however, some regions activated in one language but not in the other. These differences were revealed by a direct comparison of L1 with L2 and vice versa and were all in the right hemisphere: in the middle temporal gyrus for L1 and in the hippocampal structures and superior parietal lobule for L2. As the differences between L1 and L2 and vice versa were not observed in the HPLA bilinguals, caution should be applied in the final interpretation of these findings.

Discussion

This series of experiments provides an ample perspective for the understanding of the plasticity of the network that mediates language comprehension in the bilingual brain. The main result is that, while listening to stories in L1 and L2 yields very different patterns of cortical activity in low proficiency subjects (LPLA group), no such major difference was found in high proficiency subjects (HPLA and HPEA groups), regardless of the age of L2 acquisition. The languages spoken by the LPLA and HPLA volunteers were identical, as was the assessment procedure. Hence, we must conclude that the degree of mastery of L2 is responsible for the observed differences between the groups: auditory language comprehension in proficient bilinguals who have learned L2 after the age of 10 years relies upon a macroscopic network of areas that is similar for L1 and L2.

In addition, the strikingly similar pattern of activation observed for L1 and L2 in Italian–English and in Catalan–Spanish high proficiency bilinguals suggests that, at least at the level of resolution afforded by PET methodology, linguistic distance does not appear to play a major role in determining the degree of overlap of L1 and L2 when proficiency is very similar.

Our results must be compared with those recently reported by Kim *et al.* (1997). They used fMRI to study the representation of L1 and L2 while bilingual subjects were engaged in a silent expressive linguistic task. The volunteers had to describe what they had done during the morning, afternoon or evening of the previous day using internal speech (see also Hinke *et al.*, 1993). Twelve proficient bilinguals were studied. Of these, six had been exposed to L1 and L2 during early infancy, while six began learning L2 after puberty. A difference between our study and that by Kim *et al.* (1997) is that, while they included volunteers with different pairs of languages, our populations of bilinguals

Table 1A *HPLA bilinguals: regions activated by L1 and L2*

Activated region (BA)	L1 (Italian vs BW)				L2 (English vs BW)			
	x	*y*	*z*	*Z*-score	*x*	*y*	*z*	*Z*-score
L Superior temporal gyrus (38)	–38	12	–28	4.4	–34	12	–28	4.4
L Superior temporal gyrus (38)	–46	6	–24	4.0	–44	12	–20	4.1
L Anterior middle temporal gyrus (21)	–54	–6	–20	3.5	–46	–4	–16	3.9
L Superior temporal sulcus (22/21)	–42	–68	16	3.3	–	–	–	–
L Parahippocampal gyrus (28/35)	–	–	–	–	–26	–42	–12	4.0
L Hippocampal gyrus (35)	–	–	–	–	–34	–40	–8	3.0
L Posterior middle temporal gyrus (21)	–	–	–	–	–48	–40	0	3.7
R Parahippocampal gyrus (35)	–	–	–	–	26	–26	–16	3.9

BA = Brodmann area; L = left; R = right; BW = backwards Japanese used as control. There were no significant activations in the HPLA group when the two languages were compared with each other: (Italian versus English) and (English versus Italian).

Table 1B *HPLA and LPLA bilinguals: interactions*

Activated region (BA)	*x*	*y*	*z*	*Z*-score
HPLA (English – Silence) – LPLA (English – Silence)				
L Superior temporal gyrus (38)	–34	8	–32	2.8
L Middle temporal gyrus (21/20)	–32	–6	–20	2.5
L Superior temporal sulcus (22/21)	–32	–52	16	2.1
L Insula	–32	–18	24	2.2
R Superior temporal gyrus (38)	38	18	–24	2.2
R Middle temporal gyrus (21/20)	52	–4	–28	2.0
R Lingual gyrus (18)	28	–62	4	2.6
HPLA (English – BW) – LPLA (English – BW)				
L Superior temporal gyrus (38)	–32	6	–28	2.3
L Superior temporal sulcus (22/21)	–30	–62	8	2.0
R Parahippocampal gyrus (28/35)	22	–32	–12	4.0
R Lingual gyrus (18)	16	–62	4	3.5
R Cuneus (18)	24	–64	20	3.1
R Middle cingulate gyrus (24)	6	–14	32	3.3
R Middle temporal gyrus (21/20)	54	0	–24	2.8
R Superior temporal gyrus (38)	42	18	–24	2.4

BA = Brodmann area; L = left; R = right; BW = backwards Japanese used as control.

were more homogeneous. Kim *et al.* (1997) found that in late learners, L1 and L2 were represented in spatially segregated parts of the left inferior frontal cortex (Broca's area). However, in early learners overlapping parts of Broca's area were activated for both languages. Moreover, Kim *et al.* (1997) found that in both groups of subjects the regions activated by L1 and L2 within Wernicke's area overlapped, regardless of the age of L2 acquisition. They concluded that age of acquisition is a major factor in the cortical organization of second language processing.

Their findings are not in contradiction with our results. In the first place, Kim *et al.* (1997) used a task of unconstrained, covert language production, whereas we used a task of language comprehension. The important role of the anterior part of the perisylvian language region in language production is well known on the basis of clinical evidence (Damasio, 1992), and was recently confirmed by imaging studies (Petersen *et al.*, 1989; Wise *et al.*, 1991; Paulesu *et al.*, 1997). While the task of Kim *et al.* (1997) was associated with prominent Broca's area activation (where they report differences), our task could be expected to be associated with posterior perisylvian activation, including Wernicke's area (where they failed to find differences). We may thus possibly conclude that brain activation associated with language comprehension does not differ across languages, while the activation that is observed in production or in single-word processing tasks does. The understanding of an extended text relies heavily on lexical–semantic and conceptual processing. Most of the behavioural limitations observed with bilinguals, however, are related to phonological tasks, or to morpho/syntactic processing. The pattern of cerebral activation observed for the native language in the present study, as well as in other investigations, might reflect efficient understanding, which is strictly linked to language proficiency. This might well be compatible with subtle differences at the phonological and syntactic level reflected in Broca's area activations in the study of Kim *et al.* (1997) which, however, do not affect efficient comprehension. Secondly, there is a

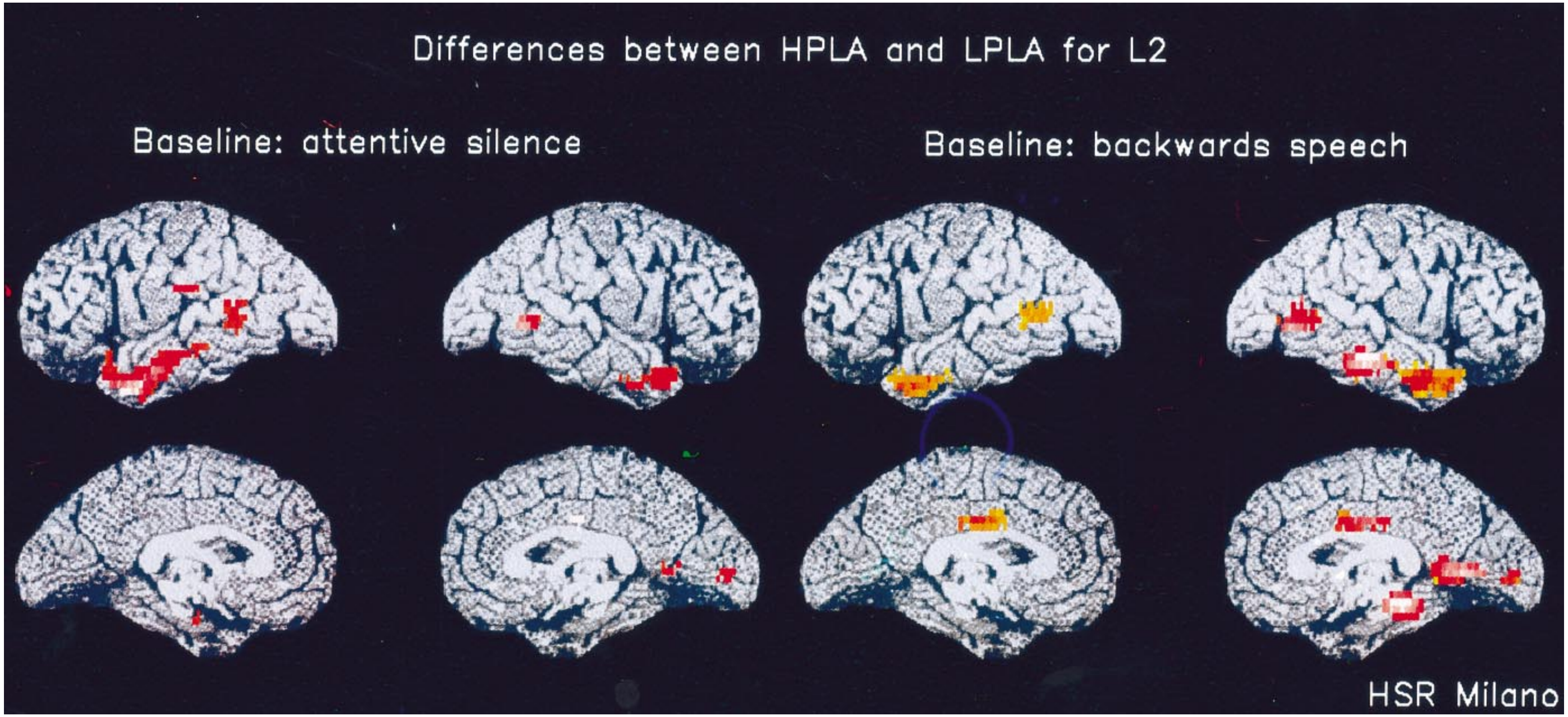

Fig. 2 Brain areas of greater activation in HPLA subjects compared with LPLA subjects for L2 (English). The group × task interaction effects are displayed as standard SPM cortical rendering. Interaction effects were computed using two different baselines: attentive silence (left half of the figure) and backwards speech. *Top row*: lateral surfaces of the brain hemispheres. *Bottom row*: mesial surfaces of the brain hemispheres. A formal anatomical description of the brain areas is given in the Results section and in Table 1.

Table 2 *HPEA bilinguals: regions activated by L1 and L2*

Activated region (BA)	L1 (L1 vs BW)				L2 (L2 vs BW)			
	x	*y*	*z*	*Z*-score	*x*	*y*	*z*	*Z*-score
L Superior temporal gyrus (38)	–46	2	–20	8.1	–48	2	–20	7.6
L Superior temporal gyrus (38)	–36	8	–28	6.2	–	–	–	–
L Superior temporal sulcus (22/21)	–46	–64	12	5.7	–50	–60	12	5.2
L Superior temporal sulcus (22/21)	–	–	–	–	–44	–70	16	4.6
L Parahippocampal gyrus (35/28)	–30	–28	–16	4.2	–20	–26	0	4.6
L Hippocampal gyrus (35)	–20	–16	–12	3.8	–26	–26	–8	4.2
L Hippocampal gyrus (35)	–20	–30	–12	3.7	–	–	–	–
L Inferior parietal lobule (40)	–26	–48	56	3.7	–	–	–	–
L Posterior middle temporal gyrus (21)	–32	–64	8	3.4	–	–	–	–
L Middle cingulate (24/32) gyrus					–10	–18	48	3.5
L Lingual gyrus/cuneus (18)	–16	–62	4	3.4	–28	–66	8	4.7
L Lingual gyrus/cuneus (18)	–22	–66	8	3.1	–	–	–	–
L Precentral gyrus (6)	–	–	–	–	–50	–10	32	3.8
R Superior temporal gyrus (38)	38	10	–24	5.1	38	–6	–24	4.8
R Superior temporal gyrus (38)	44	4	–20	5.0	–	–	–	–
R Superior temporal gyrus (38)	–	–	–	–	38	10	–24	4.3
R Superior temporal gyrus (38)	–	–	–	–	42	4	–20	4.2
R Middle cingulate (24/32) gyrus	–	–	–	–	18	–10	48	4.2
R Parahippocampal gyrus (35)	36	–14	–24	4.4	16	–36	–20	3.9
R Inferior parietal lobule (40)	–	–	–	–	28	–26	32	3.5
R/L Lingual gyrus (18)	2	–94	–8	4.0	4	–84	4	4.4
R/L Precuneus (7)	0	–50	44	3.6	–	–	–	–
R/L Cuneus (18)	0	–90	8	3.5	–	–	–	–
Cerebellar vermis	–	–	–	–	10	–40	–12	3.8
Cerebellar vermis	2	–54	–8	3.6	4	–54	–4	3.4
	L1 vs L2				L2 vs L1			
R Anterior middle temporal gyrus (21)	54	–8	–12	3.5	–	–	–	–
R Parahippocampal gyrus (35)	–	–	–	–	18	–46	–24	3.9
					14	–38	–12	3.2
R Superior parietal lobule (7)	–	–	–	–	20	–54	56	3.8
R Inferior parietal lobule (40)	–	–	–	–	32	–24	32	3.5

BA = Brodmann area; L = left; R = right; BW = the same language backwards used as control.

general negative correlation between age of acquisition and proficiency (Johnson and Newport, 1989). Since no special procedure to assess proficiency was described in the study of Kim *et al*. (1997), it is possible that the subjects who acquired L2 late were not as proficient as the subjects who had acquired L1 early in life. Hence, age of acquisition would be confounded with proficiency in this test. Finally, and we think, more importantly, their study used fMRI, whereas we used PET. The use of fMRI allows one to study brain activation subject by subject, whereas PET studies typically use group averages. With fMRI, one can detect specialized sub-regions for L1 and L2, but which differ across individuals and hence do not appear in group averages. This would account for the apparent discrepancy between the results of Kim *et al*. (1997) and those reported by others (Klein *et al*., 1994, 1995). In a PET study of a language production task (Klein *et al*., 1994), in which highly proficient French–English volunteers had to repeat or translate items in L1 or L2, differences were found only in the left putamen, not in Broca's area. The lack of differences between the effects of L1 and L2 in Broca's area in the PET studies could be due to group averaging. Similarly, a recent fMRI study by Dehaene *et al*. (1997) showed that the PET findings reported by Perani *et al*. (1996) of a reduced activation with L2 in LPLA bilinguals can be accounted for by subject variability in the cortical representation of L2. They used similar LPLA bilinguals (French–English) and the same experimental paradigm (listening to stories).

Even if we accept that apparent discrepancies between brain imaging studies can be resolved, we still have to address the issue of how to link these outcomes with behavioural studies.

The lack of differences between the cerebral activations associated with L1 and L2 in highly proficient individuals is surprising, because it seems to mesh poorly with behavioural data obtained in many different experimental settings. During the first month of life, infants learn many properties which are characteristic of the phonology of the maternal language (see Werker and Tees, 1984; Cutler *et al*., 1986, 1989, 1992; Kuhl *et al*., 1992). Not much is known about infants raised in a bilingual setting from birth. However, recent research by Bosch and Sebastian-Galles (1997) suggests that these infants make progress with both languages simultaneously, even during the first few months of life. We know, however, that if an infant is not precociously exposed to two languages she/he will become dominant in one of them and consequently will not process L2 like native speakers (see Cutler *et al.*, 1986). Moreover, Flege *et al.* (1995) claim that ‘the proportion of individuals observed to speak their L2 with a detectable accent, as well as the strength of perceived foreign accent among individuals with detectable foreign accents have been found to increase as the age of learning L2 increases’. The same researchers claim that experts notice the presence of foreign accent even when bilinguals learned L2 at a very young age. In some cases, acquisition of L2 around the age of 3 years may yield a foreign accent regardless of the amount of practice. Likewise, Weber-Fox and Neville (1996) report that bilingual English–Chinese subjects had lower accuracy judging grammar, and their event-related potentials were also affected, even though exposure to L2 occurred only 1–3 years after exposure to L1. Moreover, these subjects were of very high proficiency. Another result that goes in the same direction was recently reported by Pallier *et al.* (1997). They found that Spanish-dominant bilinguals (Spanish–Catalan, similar to the HPEA subjects who participated in this study) organize their vowel space according to the language they learned first.

How do we reconcile the discrepancy we observe between the imaging data (largely similar activations with L1 and L2 in highly proficient individuals, regardless of age of acquisition) with these behavioural findings? In the first place, we wish to raise the possibility that spatially overlapping networks to process L1 and L2 should not immediately be equated with competence, or performance identity. Best (1994) has shown that when one listens to contrasts that are not part of the native language, the outcome is different depending on the similarity between the contrast and the learned categories. If the contrast falls near an L1 category, it will be assimilated to it. Otherwise, it will be processed as in speakers of a language in which the category is instantiated. Likewise, in the case of French–English high proficiency bilinguals, the sensitivity to stress or to syllabic structure is a function of the dominant language (see Cutler *et al.*, 1989). A possible interpretation of what brain imaging is telling us is that, in the case of low proficiency individuals, multiple and variable brain regions are recruited to handle as far as possible the dimensions of L2 which are different from L1. As proficiency increases, the highly proficient bilinguals use the same neural machinery to deal with L1 and L2. However, this anatomical overlap cannot exclude the possibility that this brain network is using the linguistic structures of L1 to assimilate the dimensions of L2 less than perfectly.

It must also be pointed out that our data do not question the claim that age of acquisition is a major determinant of proficiency in L2. Indeed, as we have discussed above, many studies have found that the late learners are typically less proficient than early learners (Johnson and Newport, 1989; Flege *et al.*, 1995; Weber-Fox and Neville, 1996). What we have shown (see Fig. 3) is that when proficiency is kept constant, age of acquisition *per se* does not seem to have an impact on (macroscopic) brain representations of L2. It remains to be seen to what extent our HPLA subjects are a representative sample of bilinguals. Three of the HPLAs were highly talented professional translators and, in general, all of them were highly educated subjects. These subjects could be of high proficiency for a variety of reasons, including intensive training, and/or a greater than average degree of plasticity in language related areas. What our results show, is that for the happy few late bilinguals that reach high proficiency, the (macroscopic) brain activation is similar to that of native learners of the language. What we do not know, however, is whether the similarity in brain activation is the consequence or cause of learning L2 successfully. Further research is needed to clarify this point. As a final word of caution, it is important to recall again that, due to the limitations of PET scanning (each subject can have only a limited number of scans, typically 12–16), our observations are based only on one linguistic task (auditory story comprehension). Ideally, future experiments will assess multiple linguistic dimensions in the same subjects, a plan that only fMRI scanning may be able to accommodate, though with limited sampling of the brain (fMRI is ‘blind’ to the inferior temporal cortex and ventral frontal cortex).

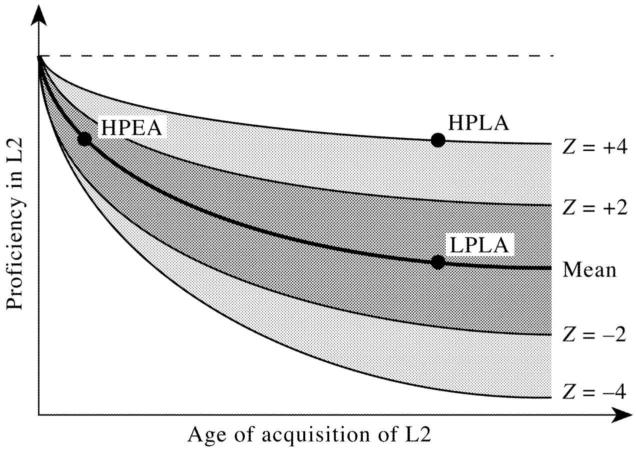

Fig. 3 Theoretical distribution of proficiency in L2 as a function of age of acquisition (Hinke *et al.*, 1993; Bosch and Sebastián, 1998). The filled cicles labelled HPEA, HPLA and LPLA represent our three groups of volunteers (i.e. high and low proficiency in L2 which was first experienced after the age of 2 years or 10 years.

Our results also have some interesting implications for the understanding of the functional/cognitive specialization of the temporal poles. These structures were consistently activated by our tasks, together with the mesial aspects belonging to the hippocampal/parahippocampal regions. Activation of the temporal poles has seldom been reported in the early functional imaging studies on language and memory (Petersen *et al.*, 1989; Wise *et al.*, 1991; Grasby *et al.*, 1993*a*). This might, in part, be attributed to technical limitations, as PET scanners that sample the entire brain and cerebellum at once have only recently become available. However, more recent language studies have shown that tasks requiring listening, or reading sentences or continuous speech (Mazoyer *et al.*, 1993; Bottini *et al.*, 1994; Fletcher *et al.*, 1995*b*; Perani *et al.*, 1996), rather than unconnected verbal material, activate the temporal poles. Accordingly we propose that these regions might be devoted to processing at the sentence level, including conceptual, syntactic and prosodic analysis.

A different but not mutually exclusive possibility is that our tasks activated these temporal lobe structures on the basis of their memory demands. Verbal memory encoding was clearly engaged by our tasks as subjects were instructed to listen to the stories in order to understand them and report details later during the post-scan interviews. Again, at variance with many other verbal memory experiments, in which unconnected verbal material was used [word lists (Grasby *et al.*, 1993*a*, *b*) or word pairs (Shallice *et al.*, 1994; Kapur *et al.*, 1996; Cabeza *et al.*, 1997; Dolan and Fletcher, 1997)], in our case subjects were engaged with the more natural task of listening to some simple narrative. Even if we consider our results in the light of the memory demands of the tasks, activation of the temporal poles might again be related to the natural language used in the tasks.

On the other hand, the activation seen in the hippocampal structures in our experiments offers a further reconciliation between lesional data and functional imaging on memory (Scoville and Milner, 1957; Press *et al.*, 1989; Fazio *et al.*, 1992; Perani *et al.*, 1993), if one considers the difficulties of detecting hippocampal involvement in most of the early PET studies on memory activation (Grasby *et al.*, 1993*a*; Shallice *et al.*, 1994).

Finally, there is an interesting discrepancy between recent experiments on verbal memory encoding and our body of results which, with the data of Perani *et al.* (1996), include four independent sets of observations. The discrepancy is the lack of consistent left lateral prefrontal cortex activation in our experiments. Indeed, a marginal activation focus near Broca's area was seen in only one comparison, in one group (L1 versus silence in the LPLA group in the study of Perani *et al.*, 1996). Thus, the proposed functional specialisation of the left dorsolateral prefrontal cortex for operations active during encoding may need to be constrained to the particular paradigms in which those activations were observed (Shallice *et al.*, 1994; Tulving *et al.*, 1994; Fletcher *et al.*, 1995*a*; Kapur *et al.*, 1996; Cabeza *et al.*, 1997). One possibility is that the left prefrontal cortex may be involved in memory encoding because of its more general role in planning/executive functions, i.e. when arbitrary links between items need to be made. This hypothesis is consistent with the dual-task interference effect demonstrated by Shallice *et al.* (1994) in left prefrontal cortex at encoding, and is supported by recent direct evidence provided by Dolan and Fletcher (1997). Our findings, which concur with the idea that the left prefrontal cortex is not necessary for all forms of verbal memory encoding, are also consistent with the observation that patients with bilateral frontal lobe lesions can show normal performance in standard tests of recognition and recall (Petrides, 1996).

Acknowledgements

We wish to thank Dr Andrea Moro for discussion and Giuseppe Striano for technical assistance. This work was supported by grants from HFSP, CNR and CNRS.

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Received October 28, 1997. Revised April 4, 1998.
Accepted May 20, 1998