

WE used positron emission tomography to study brain activity in adults while they were listening to stories in their native language, in a second language acquired after the age of seven, and in a third unknown language. Several areas, similar to those previously observed in monolinguals, were activated by the native but not by the second language. Both the second and the unknown language yielded distinct left-hemispheric activations in areas specialized for phonological processing, which were not engaged by a backward speech control task. These results indicate that some brain areas are shaped by early exposure to the maternal language, and are not necessarily activated by the processing of a second language to which they have been exposed for a limited time later in life.

Key words: Bilingualism; Cognitive processes; Language acquisition; Positron emission tomography

Brain processing of native and foreign languages

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Introduction

Language acquisition has been defined as the result of a dedicated cerebral 'organ'¹ that becomes attuned to the processing of the native language during the first years of life.²⁻⁴ Although humans may learn more than one language, the second language is often spoken with reduced fluency and with a perceptible foreign accent.^{5,6} Neuropsychological studies indicate that, in polyglots, aphasia can differentially affect either of the languages;⁷ it is debatable whether this is due to a specialization of distinct brain areas for different languages, or whether it merely reflects social and environmental factors.

Our study aimed to evaluate the features of the human brain endowment for language. Positron emission tomography was used to study brain activity while bilingual adults listened to stories in their native language, in a second language acquired after 7 years of age, or in a third unknown language.

Subjects and Methods

Subjects: Nine right-handed male Italians, native speakers of Italian, aged between 21 and 32 years, participated in the study after giving their written informed consent. The experimental protocol was approved by the local hospital Ethics Committee. All subjects were born of Italian parents and had studied English at school for at least 5 years. They had not been exposed to English before the age of 7 years, nor had they spent more than 1 month in an English-

speaking country. To be included in the study, subjects had to have a good understanding of spoken English, as assessed by word translation and sentence comprehension tests. None of them had any knowledge of the Japanese language.

Cerebral blood flow (CBF) was assessed with positron emission tomography (PET) while normal subjects listened to short stories in Italian, English or Japanese, recorded by monolingual male speakers with comparable speech rate, pitch, intonation and intensity. Two control conditions were also run. In the first, subjects listened to the Japanese tapes played backwards (backwards condition). In the second, subjects paid attention while infrequent vowel sounds were played at random 10-40 s intervals (attentive rest). To ensure adequate attention, subjects were warned that they would have to answer questions about the meaning of the stories (Italian and English) or the perceptual characteristics of the stimuli (other conditions) after each scan. Out of 10 difficult factual questions referring to the stories heard during PET scanning, the subjects averaged eight correct responses in Italian and 6.5 correct in the second language, indicating that English comprehension was only slightly worse than Italian.

PET procedures: Scans were obtained using a PET tomograph GE-Advance (General Electric Medical System, Milwaukee, WI).⁸ The system has 18 rings which allows 35 transaxial images to be obtained with a slice thickness of 4.25 mm covering an axial field of view of 15.2 cm. The system has the ability to acquire data in a two- or three-dimensional

scanning mode by using retractable tungsten septa. Transmission data were acquired using a pair of rotating pin sources filled with ^{68}Ge (10 mCi per pin). A filtered back-projection algorithm was employed for image reconstruction, on a 128×128 matrix with a pixel size of 1.9 mm, using a Hanning filter (cutoff 4 mm filter width) in the transaxial plane, and a Ramp filter (cutoff 8.5 mm) in the axial direction. MR imaging was performed on a GE-Signa (General Electric Medical System, Milwaukee, WI) operating at 1.5 T. A Spoiled Grass (SPGR) sequence was used for three-dimensional volume acquisition. Transaxial acquisition was performed for each subject. The acquisition parameters for the SPGR sequence were: TR = 17.4 ms, TE = 6.6 ms, TI = 700 ms, flip angle = 10° , FOV: 240 mm, sections: 124, image matrix: 256×256 , pixel size: 0.94 mm, slice thickness: 1.5 mm. Once reconstructed the images were transferred to a SUN image workstation (SUN Microsystems Inc.).

rCBF was measured by recording the distribution of radioactivity following an i.v. bolus injection of 1110 MBq [^{15}O]H₂O through a forearm cannula. The integrated counts collected for 90 s, starting 30 s after injection, were used as an index of rCBF; 10 scans

related to the different experimental conditions acquired for each subject. rCBF measurements were taken during a single scanning session lasting about 2.5 h.

Each subject performed three linguistic tasks (listening to Italian, English, and Japanese stories) and two control tasks (listening to Japanese backwards and attentive rest). Subjects underwent 10 consecutive scans, two for each (3 min) psychological condition. Task sequence was randomized across subjects.

Data analysis:

Image manipulations and statistical analysis were performed in MATLAB 4.2 (Math Works, Natick, MA, USA) using statistical parametric mapping (SPM-95, MRC Cyclotron Unit, London, UK). Head movement between PET scans was corrected by aligning the scan for each subject with the first one recorded using Automated Image Registration (AIR) software.⁹ Individual PET data were co-registered onto individual MRI data oriented along the inter-commissural line.¹⁰ These MRI and PET images were then transformed into a standard stereotactic space;¹¹ global differences in CBF were co-varied out for

Table 1. Areas activated while listening to different languages compared with the condition of attentive silence

	x	y	z	Z score	Location
Italian	-48	10	-16	7.30	L temporal pole (Ba 38)
	-58	-24	4	7.17	L superior temporal gyrus (Ba 22)
	-46	-72	20	3.60	L inferior parietal gyrus (Ba 39)
	-50	-20	0	7.23	L mid-temporal gyrus (Ba 21)
	62	-12	0	7.26	R superior temporal gyrus (Ba 22)
	54	4	-16	6.09	R temporal pole (Ba 38)
	58	0	-8	6.12	R mid-temporal gyrus (Ba 21)
	-2	-56	24	2.92	L posterior cingulate (Ba 31)
	-46	32	0	2.70	L inferior frontal gyrus (Ba 45)
	24	-88	-36	2.90	R cerebellar hemisphere
English	60	-10	0	8.65	R mid-temporal gyrus (Ba 21)
	-50	-20	0	7.45	L mid-temporal gyrus (Ba 21)
	44	-28	4	5.58	R superior temporal gyrus (Ba 22)
	-58	-24	4	7.71	L superior temporal gyrus (Ba 22)
	-24	-34	-20	2.98	L parahippocampus (Ba 36)
	8	-32	-12	2.90	R parahippocampus (Ba 36)
Japanese	62	-14	0	8.26	R mid-temporal gyrus (Ba 21)
	-60	-14	0	6.96	L mid-temporal gyrus (Ba 21)
	62	-42	12	3.27	R superior temporal gyrus (Ba 22)
	-60	-30	8	7.28	L superior temporal gyrus (Ba 22)
	-46	-16	0	7.66	L superior temporal gyrus (Ba 22) (temporal operculum)
	22	0	-32	3.48	R parahippocampus (Ba 36)
Backwards	62	-12	4	9.55	R superior temporal gyrus (Ba 22)
	-54	-22	4	6.72	L superior temporal gyrus (Ba 22)
	18	-32	-16	3.43	R parahippocampal gyrus (Ba 36)
	0	-54	28	2.98	R/L posterior cingulate

Co-ordinates in mm refer to the location in the stereotactic space of the maximal activity indicated by the highest Z scores in a particular activated cerebral structure (threshold for significance: Z score ≥ 2.70 ; $p \geq 0.01$). Numbers in parentheses refer to Brodmann areas and do not imply cytoarchitectonic correlates and are used only to assist in the localization of brain activity. Abbreviations: R, right; L, left.

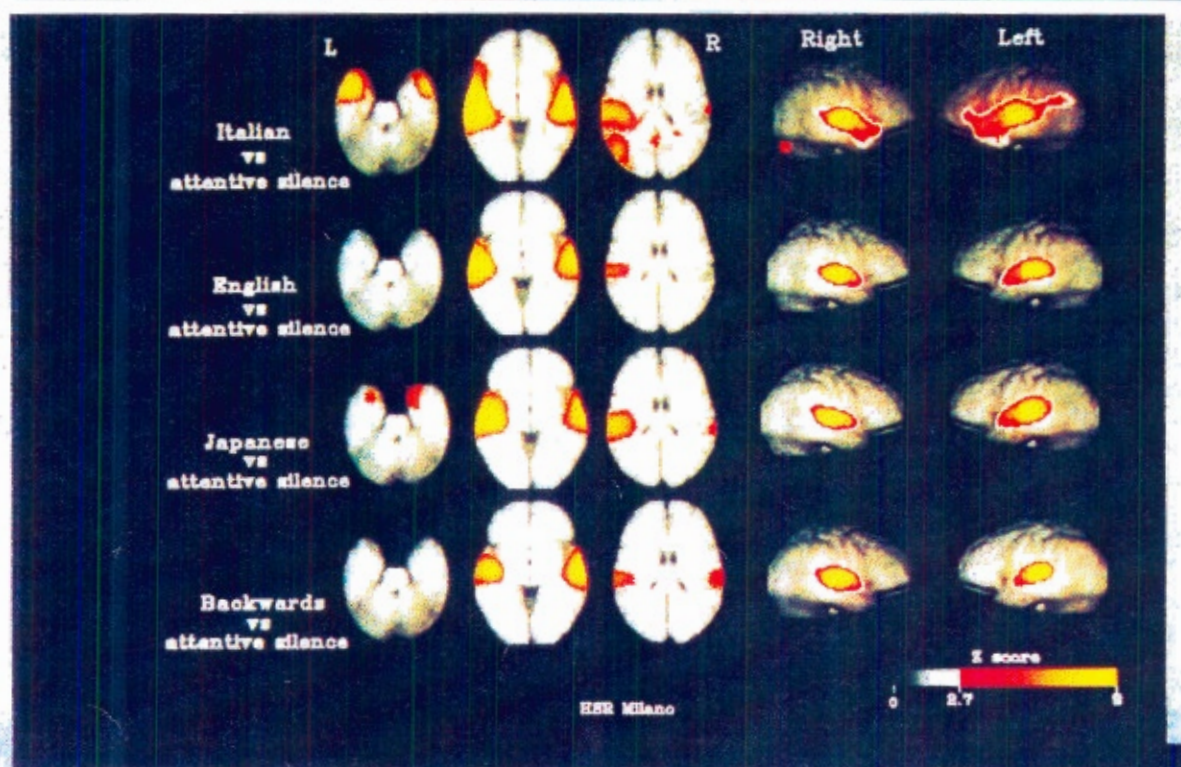


FIG. 1. Activations related to the processing of Italian language (mother tongue), the second language (English), and the unknown language (Japanese) when compared with the attentive silence condition. The areas of significant activation are plotted on averaged MRI images from all experimental subjects transformed into the stereotactic space of Talairach and Tournoux.¹¹ Three representative axial slices and lateral projections of the left and right cortical surfaces are shown. The activated areas are displayed in a linear colour scale. Stereotactic coordinates and level of significance expressed as Z scores are reported in Table 1.

all voxels and comparisons across conditions using *t*-statistics with appropriate linear contrasts.¹² Only regional activations significant at $p \leq 0.01$ (uncorrected for multiple non-independent comparisons or for the size of activation foci) were considered.

The stereotactic coordinates of the relevant activation foci shown in the categorical comparisons were used to build activation profiles relative to the four experimental conditions and attentive silence.

Results

Brain areas involved in native language comprehension were identified by comparing the Italian condition with attentive rest. In the left hemisphere, activation was seen in the classical perisylvian language areas, including the angular gyrus (Brodmann area 39), the superior and middle temporal gyri (Ba 22 and 21) and the inferior frontal gyrus (Ba 45), plus the temporal pole (Ba 38). The right superior and middle temporal gyri (Ba 21/22), the right temporal pole (Ba 38), the posterior cingulate (Ba 31) and a focus in the right cerebellum were also significantly activated. This pattern closely replicates earlier studies in which French and English subjects, respectively, were scanned while listening to stories in their native

languages^{13,14} and represents the cerebral network activated by the processing of extended prose. The same analysis was applied to the second-language

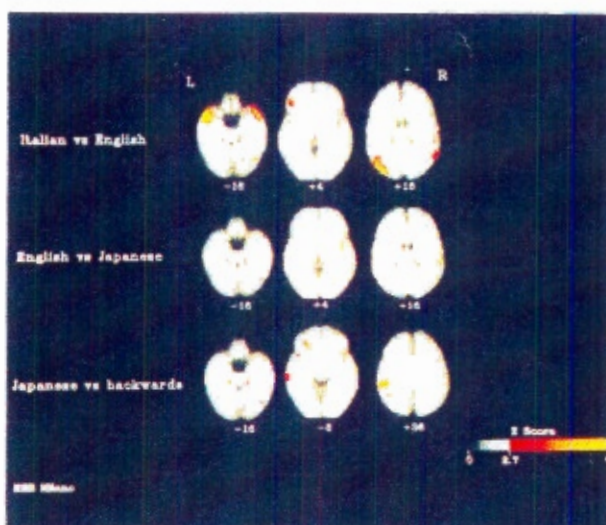


FIG. 2. A top-to-down comparison was performed from the better known language to the backward condition. The activated areas displayed in a linear colour scale are shown on three representative axial slices of averaged MRI images. Stereotactic coordinates and level of significance expressed as Z scores are reported in Table 2.

Table 2. Comparison of areas activated while listening to different languages

	x	y	z	Z score	Location
Italian vs Japanese	48	14	-20	3.35	R temporal pole (Ba 38)
	-46	10	-16	4.33	L temporal pole (Ba 38)
	-38	38	4	2.76	L inferior frontal gyrus (Ba 45)
	-28	-90	16	3.61	L mid-occipital gyrus (Ba 19)
	-44	-76	24	3.60	L inferior parietal lobule (Ba 39)
	54	-62	12	2.81	R inferior parietal/temporal lobe (Ba 39/21)
English vs Japanese	No significant activated areas				
Japanese vs backwards	-24	30	-8	3.20	L inferior frontal gyrus (Ba 47)
	-42	-30	24	3.14	L inferior parietal lobule (Ba 39)
	-40	-58	40	3.06	L inferior parietal lobule (Ba 40)
	-62	-24	-8	2.70	L mid-temporal gyrus (Ba 21)
Italian vs backwards	-48	10	-16	5.74	L temporal pole (Ba 38)
	52	8	-16	3.88	R temporal pole (Ba 38)
	-46	-72	20	4.05	L inferior parietal lobule (Ba 39)
	-56	-40	0	3.25	L mid-temporal gyrus (Ba 21)
	-36	-80	16	3.04	L mid-occipital gyrus (Ba 19)
English vs backwards	-56	-40	0	3.60	L mid-temporal gyrus (Ba 21)
Japanese vs English	-40	-60	36	3.99	L inferior parietal lobule (Ba 39)
	-34	50	12	3.51	L mid-frontal gyrus (Ba 10)
	22	6	-24	3.27	R parahippocampal gyrus (Ba 36)
	-36	-2	-4	2.97	L superior temporal gyrus (Ba 22) (temporal operculum)
Italian vs Japanese	-48	10	-16	5.16	L temporal pole (Ba 38)
	52	6	-20	5.09	R temporal pole (Ba 38)
	26	-58	8	3.56	R posterior cingulate (Ba 31)
	-42	-72	20	3.32	L inferior parietal lobule (Ba 39)
Backwards vs Japanese	62	-12	12	3.45	R superior temporal gyrus (Ba 22)
	24	-36	-16	3.36	R parahippocampus (Ba 36)
	18	-50	0	3.57	R lingual gyrus (Ba 18)

Co-ordinates in mm refer to the location in the stereotaxic space of the maximal activity indicated by the highest Z scores in a particular activated cerebral structure (threshold for significance: Z score ≥ 2.70 ; $p \geq 0.01$). Numbers in parentheses refer to Brodmann areas and do not imply cytoarchitectonic correlates and are used only to assist in the localization of brain activity. Abbreviations: R, right; L, left.

condition (English). The set of active language areas was considerably reduced. Only the left and right superior and middle temporal areas (Ba 22 and 21) remained active. There was also a minor bilateral activation of parahippocampal gyri (Ba 36), suggesting an increased participation of memory-related structures.¹⁵ The activations observed while listening to English did not extend beyond those observed in the unknown language, Japanese. Relative to the attentive rest condition, listening to Japanese activated the left and right superior and middle temporal regions (Ba 22 and 21) and an additional focus in the right mesial anterior temporal region (Ba 36/20; Fig. 1, Table 1).

Direct comparison of brain activations during listening to Italian and to English confirmed that a large set of areas was significantly more active for the native language, including the left inferior parieto-occipital area (Ba 39/19), the left and right temporal poles (Ba 38), and the left inferior frontal gyrus

(Ba 45). No single region was significantly more active while listening to English rather than Japanese. This was so even though our subjects clearly understood the English, though not the Japanese stories (Fig. 2, Table 2).

rCBF increased in attentive silence compared with backward and all language conditions pooled together (Table 3). The significant foci were located bilaterally in the inferior parietal lobule and in the superior frontal gyrus and the cuneus, in the right hemisphere. These can also be considered as regions of deactivation for the other conditions.

The activation profiles confirmed the prevalent activation of the left inferior frontal, left inferior parietal and bilateral temporal poles while subjects listened to the story in Italian (Fig. 3). In contrast, bilateral activation of the superior and middle temporal gyri was present during all experimental conditions when compared with the attentive silence condition (Fig. 4).

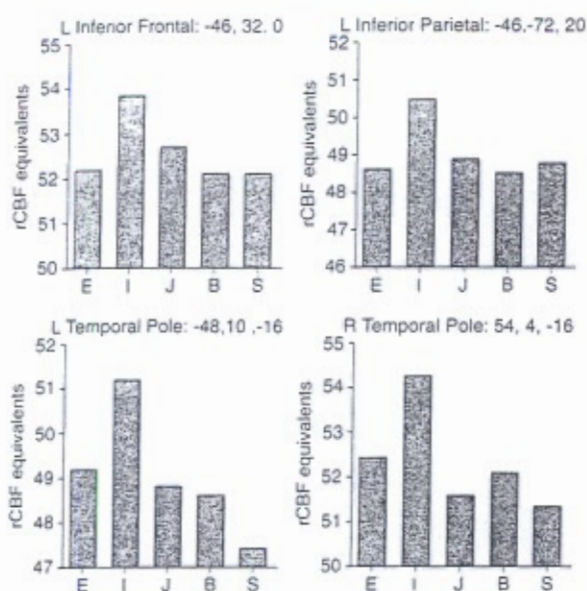


FIG. 3. Plots of rCBF activation profiles relative to the defined activation foci for the four experimental conditions and the attentive silence. Abbreviations: I, Italian; E, English; J, Japanese; B, backward; A, attentive silence; R, right; L, left.

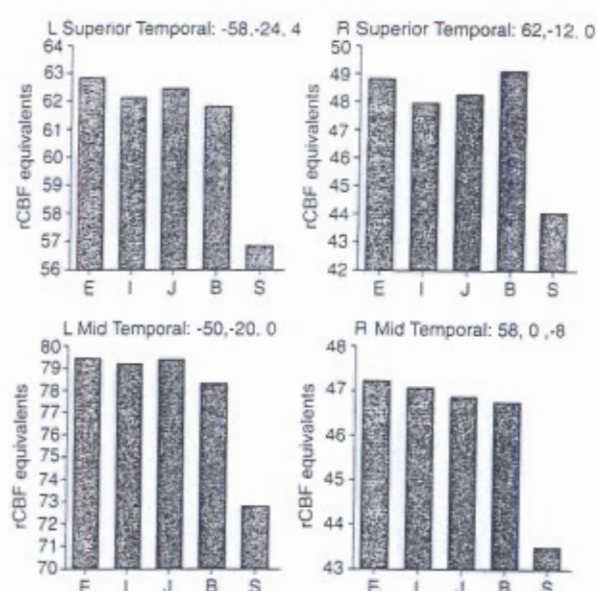


FIG. 4. Plots of rCBF activation profiles relative to the defined activation foci for the four experimental conditions and the attentive silence. Abbreviations: I, Italian; E, English; J, Japanese; B, backward; A, attentive silence; R, right; L, left.

Discussion

The finding of partially different cerebral substrates for the first and second language is compatible with previous studies using direct electrical cortical stimulation during naming tasks in bilingual individuals.^{16,17} In seven patients, sites were found where stimulation disrupted naming in one language, but not in the other. Event-related potentials and activation studies with functional magnetic resonance imaging have also revealed considerable differences in the cerebral organization of native and non-native users of sign language.¹⁸ By contrast, one previous study using PET found very little difference between the first and the second language, apart from a left putaminal focus when speaking in the second

language.¹⁹ Only single-word processing however, was assessed in this study, whereas we found the largest differences between the first and second languages in areas such as the temporal poles that have been related to sentence-level processing.¹³ In addition, the Canadian subjects used in that study¹⁹ were almost as fluent in their second language (French) as in their first language (English). Further work varying the initial age of exposure and the degree of mastery of the second language should clarify the time course of brain plasticity for language. A previous study²⁰ found extensive left-hemispheric regions of activation for English sentences, including the left temporal pole, in subjects who were native speakers of English. Hence, the low level of activity we observed in the English condition was probably

Table 3. Comparison of activation while listening to any language or backwards language

	x	y	z	Z score	Location
Attentive silence vs backwards	54	-46	40	4.92	R inferior parietal lobule (Ba 40)
	-44	-56	40	4.65	L inferior parietal lobule (Ba 40)
Attentive silence vs all languages combined	54	-46	40	6.91	R inferior parietal lobule (Ba 40)
	-32	-60	36	5.03	L inferior parietal lobule (Ba 40)
	22	2	60	4.10	R superior frontal gyrus (Ba 6)
	32	58	4	4.28	R mid-frontal gyrus (Ba 10)
	14	-80	36	4.17	R cuneus (Ba 19)

Co-ordinates in mm refer to the location in the stereotactic space of the maximal activity indicated by the highest Z scores in a particular activated cerebral structure (threshold for significance: Z score ≥ 2.70 ; $p \geq 0.01$). Numbers in parentheses refer to Brodmann areas and do not imply cytoarchitectonic correlates and are used only to assist in the localization of brain activity. Abbreviations: R, right; L, left.

not due to some intrinsic property of the English language, but to English being our subjects' second language.

The selective response of a network of cerebral areas, including left hemispheric regions (the inferior frontal cortex and the parieto-occipital areas) and the temporal poles bilaterally, to Italian as opposed to English and Japanese, implies that the organization of these areas has been shaped by exposure to the native language during childhood. Decreased neuronal plasticity within these areas might be the cerebral substrate of the 'sensitive period' in language acquisition.⁶ Our results merely show that these areas are not responsive to a second language acquired after the age of 7 years. We cannot exclude that they will eventually respond to a second language if it becomes the main language of use for many years.

Another striking result of this study is that no brain areas were significantly more active when listening to stories in English than when listening to an unknown language, Japanese. This was an unexpected finding, given the behavioural evidence that subjects analysed stories in English up to lexical, syntactic and pragmatic levels. Two non-mutually exclusive interpretations might account for this result. First, some brain areas underlying second-language comprehension might have remained undetected, possibly because of weaker activation. A second possibility is that, while the native language recruits similar cortical structures in all subjects, the regions involved in processing a second language show greater inter-individual variability and therefore fail to stand out when averaged across subjects. Electrical stimulation^{16,17} and neuropsychological studies⁷ have indeed shown a considerable degree of variability in the neural substrates of the second language.

Our paradigm also permitted us to identify brain areas that are specialized for speech processing in both native and non-native languages. When the condition in which subjects listened to the Japanese tapes played backwards was compared with the attentive silence condition, there was bilateral activation in both superior temporal gyri (Ba 22; Fig. 1). This activation, however, was greater in the right hemisphere, contrary to the left-hemispheric superiority that prevailed in all three conditions with normal forward speech. A direct comparison showed that several left-hemispheric areas were significantly more active while listening to forward rather than to backward Japanese: the inferior parietal lobule (Ba 39/40), a small inferior frontal area (Ba 47), and the middle temporal gyrus (Ba 21). These activations may reflect

in part the subjects' attempt to store the input as meaningless phonological information in auditory-verbal short-term memory.²¹ Most importantly, the left middle temporal gyrus activation appeared in all conditions of stimulation with forward speech (Italian, English and Japanese; see Table 1), but not while listening to backward speech, an acoustically similar but phonologically impossible stimulus. This area thus contrasts sharply with other language areas because it is both highly selective to the phonology or prosody of speech in any language and yet not specialized for the native language.

Conclusion

Our study illuminates two features of the endowment of the human brain for language. Some areas distinguish spoken language from non-speech verbal inputs, irrespective of any knowledge of the language itself, and they maintain this ability through adulthood. Several other brain areas are shaped by early exposure to the maternal language, and are not necessarily activated when subjects are engaged in the processing of a second language, which they have learned through limited exposure later in life.

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