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

Introduction

Language acquisition has been defined as the result of a dedicated cerebral ‘organ’ that becomes attuned to the processing of the native language during the first years of life. Although humans may learn more than one language, the second language is often spoken with reduced fluency and with a perceptible foreign accent. Neuropsychological studies indicate that, in polyglots, aphasia can differentially affect either of the languages; 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). 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 retracted tungsten septa. Transmission data were acquired using a pair of rotating pin sources filled with $^{11}$C (10 mCi per pin). A filtered back-projection algorithm was employed for image reconstruction, on a 128 x 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:

\[
\begin{align*}
T_R = 17.4 \text{ ms}, \hspace{1cm} T_E = 6.6 \text{ ms}, \hspace{1cm} T_I = 700 \text{ ms}, \hspace{1cm} \text{ Flip angle} = 15^\circ, \hspace{1cm} \text{FOV: 240 mm}, \hspace{1cm} \text{sections: 124}, \hspace{1cm} \text{image matrix: 256 \times 256}, \hspace{1cm} \text{pixel size: 0.94 mm}, \hspace{1cm} \text{slice thickness: 1.5 mm}.
\end{align*}
\]

Once reconstructed the images were transferred to a SUN image workstation (SUN Microsystems Inc.).

rCBF was measured by registering the distribution of radioactivity following an i.v. bolus injection of 1110 MBq $^{18}$O$^2$H$^2$O 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, RMC 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. Individual PET data were co-registered onto individual MRI data oriented along the intercommissural line. These MRI and PET images were then transformed into a standard stereotactic space; regional differences in CBF were co-varied out for

<p>| Table 1. Areas activated while listening to different languages compared with the condition of attentive silence |
|---|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>$x$</th>
<th>$y$</th>
<th>$z$</th>
<th>$Z$ score</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Italian</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-45</td>
<td>-10</td>
<td>-16</td>
<td>7.30</td>
<td>L temporal pole (Broca's)</td>
</tr>
<tr>
<td>-65</td>
<td>-24</td>
<td>4</td>
<td>7.17</td>
<td>L superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-65</td>
<td>-12</td>
<td>20</td>
<td>3.60</td>
<td>L inferior parietal gyrus (Broca's)</td>
</tr>
<tr>
<td>-50</td>
<td>-20</td>
<td>0</td>
<td>7.23</td>
<td>L mid-temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>52</td>
<td>-16</td>
<td>0</td>
<td>7.55</td>
<td>R superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>-16</td>
<td>5.89</td>
<td>R temporal pole (Broca's)</td>
</tr>
<tr>
<td>88</td>
<td>0</td>
<td>-8</td>
<td>5.12</td>
<td>R mid-temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-2</td>
<td>-56</td>
<td>24</td>
<td>2.92</td>
<td>L posterior cingulate (Broca's)</td>
</tr>
<tr>
<td>-46</td>
<td>-32</td>
<td>0</td>
<td>2.70</td>
<td>L inferior frontal gyrus (Broca's)</td>
</tr>
<tr>
<td>24</td>
<td>-56</td>
<td>-36</td>
<td>2.90</td>
<td>R cerebellar hemisphere</td>
</tr>
<tr>
<td><strong>English</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>-10</td>
<td>0</td>
<td>8.05</td>
<td>R mid-temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-50</td>
<td>-20</td>
<td>0</td>
<td>7.45</td>
<td>L mid-temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>44</td>
<td>-28</td>
<td>4</td>
<td>5.58</td>
<td>R superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-58</td>
<td>-24</td>
<td>4</td>
<td>7.11</td>
<td>L superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-24</td>
<td>-34</td>
<td>-20</td>
<td>2.98</td>
<td>L parahippocampus (Broca's)</td>
</tr>
<tr>
<td>8</td>
<td>-32</td>
<td>-12</td>
<td>2.90</td>
<td>R parahippocampus (Broca's)</td>
</tr>
<tr>
<td><strong>Japanese</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>-14</td>
<td>0</td>
<td>8.26</td>
<td>R mid-temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-60</td>
<td>-14</td>
<td>0</td>
<td>6.96</td>
<td>L mid-temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>37</td>
<td>-22</td>
<td>12</td>
<td>3.73</td>
<td>R superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-65</td>
<td>-10</td>
<td>6</td>
<td>7.28</td>
<td>L superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-40</td>
<td>-16</td>
<td>0</td>
<td>7.06</td>
<td>L temporal operculum (Broca's)</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>-32</td>
<td>3.48</td>
<td>R parahippocampus (Broca's)</td>
</tr>
<tr>
<td><strong>Backwards</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>-12</td>
<td>4</td>
<td>5.55</td>
<td>R superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>-54</td>
<td>-22</td>
<td>4</td>
<td>6.72</td>
<td>L superior temporal gyrus (Broca's)</td>
</tr>
<tr>
<td>18</td>
<td>-32</td>
<td>-16</td>
<td>3.44</td>
<td>R parahippocampus (Broca's)</td>
</tr>
<tr>
<td>0</td>
<td>-54</td>
<td>26</td>
<td>2.96</td>
<td>R posterior cingulate</td>
</tr>
</tbody>
</table>

Coordinates 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 $\geq 2.70$, p $< 0.01$). 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 as averaged MRI images from all experimental subjects.
Table 2. Comparison of areas activated while listening to different languages

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Z score</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italian vs Japanese</td>
<td>-45</td>
<td>14</td>
<td>-20</td>
<td>3.35</td>
<td>R temporal pole (BA 38)</td>
</tr>
<tr>
<td></td>
<td>-48</td>
<td>10</td>
<td>-16</td>
<td>4.33</td>
<td>L temporal pole (BA 38)</td>
</tr>
<tr>
<td></td>
<td>-36</td>
<td>38</td>
<td>4</td>
<td>2.70</td>
<td>L inferior frontal gyrus (BA 45)</td>
</tr>
<tr>
<td></td>
<td>-29</td>
<td>-90</td>
<td>16</td>
<td>3.61</td>
<td>L mid-occipital gyrus (BA 19)</td>
</tr>
<tr>
<td></td>
<td>-44</td>
<td>-76</td>
<td>24</td>
<td>3.60</td>
<td>L inferior parietal lobule (BA 39)</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>-62</td>
<td>12</td>
<td>2.61</td>
<td>R inferior parietal/temporal lobe (BA 39/21)</td>
</tr>
<tr>
<td>English vs Japanese</td>
<td>No significant activated areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japanese vs backwards</td>
<td>-24</td>
<td>30</td>
<td>-8</td>
<td>3.20</td>
<td>L inferior frontal gyrus (BA 47)</td>
</tr>
<tr>
<td></td>
<td>-42</td>
<td>-36</td>
<td>24</td>
<td>3.14</td>
<td>L inferior parietal lobule (BA 39)</td>
</tr>
<tr>
<td></td>
<td>-40</td>
<td>-68</td>
<td>40</td>
<td>3.06</td>
<td>L inferior parietal lobule (BA 40)</td>
</tr>
<tr>
<td></td>
<td>-62</td>
<td>-24</td>
<td>-8</td>
<td>2.70</td>
<td>L mid-temporal gyrus (BA 22)</td>
</tr>
<tr>
<td>Italian vs backwards</td>
<td>-42</td>
<td>10</td>
<td>-15</td>
<td>3.14</td>
<td>L temporal pole (BA 38)</td>
</tr>
<tr>
<td></td>
<td>-32</td>
<td>20</td>
<td>13</td>
<td>2.84</td>
<td>L temporal pole (BA 38)</td>
</tr>
<tr>
<td></td>
<td>-65</td>
<td>-72</td>
<td>20</td>
<td>4.06</td>
<td>L inferior occipital (BA 39)</td>
</tr>
<tr>
<td></td>
<td>-35</td>
<td>40</td>
<td>0</td>
<td>3.21</td>
<td>L mid-temporal gyrus (BA 21)</td>
</tr>
<tr>
<td></td>
<td>-35</td>
<td>40</td>
<td>0</td>
<td>3.21</td>
<td>L mid-temporal gyrus (BA 39)</td>
</tr>
<tr>
<td>Japanese vs English</td>
<td>-48</td>
<td>-60</td>
<td>25</td>
<td>3.29</td>
<td>L superior temporal gyrus (BA 39)</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>-60</td>
<td>12</td>
<td>3.29</td>
<td>L superior temporal gyrus (BA 22)</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>24</td>
<td>12</td>
<td>2.87</td>
<td>L parietal cortex (BA 39)</td>
</tr>
<tr>
<td></td>
<td>-36</td>
<td>-7</td>
<td>-14</td>
<td>3.17</td>
<td>L superior temporal gyrus (BA 22)</td>
</tr>
<tr>
<td>Italian vs Japanese</td>
<td>-42</td>
<td>10</td>
<td>15</td>
<td>3.10</td>
<td>L temporal pole (BA 38)</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>6</td>
<td>-20</td>
<td>5.06</td>
<td>L temporal pole (BA 38)</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>65</td>
<td>18</td>
<td>5.16</td>
<td>R inferior occipital (BA 31)</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>-72</td>
<td>20</td>
<td>3.32</td>
<td>R superior temporal gyrus (BA 39)</td>
</tr>
<tr>
<td>Japanese vs backwards</td>
<td>92</td>
<td>-13</td>
<td>12</td>
<td>3.45</td>
<td>R superior temporal gyrus (BA 22)</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>-38</td>
<td>-15</td>
<td>3.28</td>
<td>R superior temporal gyrus (BA 39)</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>-62</td>
<td>0</td>
<td>2.67</td>
<td>R inferior parietal (BA 39)</td>
</tr>
</tbody>
</table>

Coordinates in mm refer to the location in the stereotactic space of the maximal activity revealed by the highest Z score. A particular activated area of a given structure is highlighted for significances above Z = 2.33, p < 0.01. Numbers in parentheses refer to Brodmann areas and do not signify cytoarchitectonic correlates. Coordinates are only approximate. In the localization of the activity, Abbreviations: BA, Brodmann Area.

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 strong bilateral activation of parahippocampal areas (BA 30). These suggest an increased participation of memory-related structures. This was not observed while listening to English, which is not as widely known than Italian. Relative to the receptive condition, listening to Japanese activates the left and right anterior and middle temporal regions (BA 22 and 21) and an additional focus in the right middle/inferior temporal region (BA 36/37, 41, 40, 39). However, conditions (English) suggested a more highly active language including the left inferior parietal cortex than the left inferior frontal, which was not the case with the receptive condition (see Table 1).
A PET study of bilingualism

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. 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. By contrast, one previous study using PET found very little difference between the first and second language, apart from a left putaminal focus when speaking in the second language. 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. In addition, the Canadian subjects used in that study 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 study 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

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Z score</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attentive silence vs backwards</td>
<td>54</td>
<td>-46</td>
<td>40</td>
<td>4.92</td>
<td>R inferior parietal lobule (BA 40)</td>
</tr>
<tr>
<td></td>
<td>-41</td>
<td>-56</td>
<td>40</td>
<td>4.65</td>
<td>L inferior parietal lobule (BA 40)</td>
</tr>
<tr>
<td>Attentive silence vs all languages combined</td>
<td>54</td>
<td>-46</td>
<td>40</td>
<td>8.91</td>
<td>R inferior parietal lobule (BA 40)</td>
</tr>
<tr>
<td></td>
<td>-32</td>
<td>-60</td>
<td>36</td>
<td>5.03</td>
<td>L inferior parietal lobule (BA 40)</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>2</td>
<td>60</td>
<td>4.10</td>
<td>R superior frontal gyrus (BA 6)</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>58</td>
<td>4</td>
<td>4.28</td>
<td>R mid-frontal gyrus (BA 10)</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>-89</td>
<td>56</td>
<td>4.17</td>
<td>R cuneus (BA 19)</td>
</tr>
</tbody>
</table>

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 ≤ 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. 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 behavioral evidence that subjects analyzed 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 and neuropsychological studies 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 lobe (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.

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.

References

Received 8 May 1996; accepted 18 June 1996.