Inferring native language from early bio-electrical activity

Proverbio Alice Mado a, *, Roberta Adorni a, Alberto Zani b

a Department of Psychology, University of Milano-Bicocca, Via dell’Innovazione 10, 20126 Milan, Italy
b Institute of Bioimaging and Molecular Physiology, CNR, Milano-Segrate, Italy

1. Introduction

One of the most debated issues in Cognitive Neuroscience is how multiple languages are represented in the human brain (e.g., Hernandez et al., 2005; Crinion et al., 2006). The search for a neural network of linguistic brain regions involved in the various aspects of language comprehension, reading and production is complicated by factors such as the level of proficiency attained for both foreign or native languages, age of acquisition of both, exposure to different linguistic environments, context of acquisition (affective, scholar, professional, etc.), and the interactions among these factors (Proverbio et al., 2007).

Some studies seem to support the notion that, proficiency being equal, there is no macroscopic difference in the ways different languages are processed by balanced proficient bilinguals, in particular no gross effect of age of acquisition (Crinion et al., 2006; Hernandez et al., 2000; Illies et al., 1999; Paradis, 1996; Perani and Abutalebi, 2005; Perani et al., 1998). Other studies do not support this view, and instead provide evidence of marked differences in the timing of activation and anatomical recruitment of brain areas for processing languages acquired at different ages and in different contexts (Chee et al., 2003, 2004; Roux et al., 2004; Dehaene et al., 1997; Gomez-Tortosa et al., 1995; Lucas et al., 2004; Proverbio et al., 2002, 2004, 2007).

One of the most crucial factors seems to be the age of linguistic learning and its interaction with the ongoing acquisition of conceptual knowledge in children (Dufour and Kroll, 1995). Indeed, early language learners implicitly (and instinctively) associate the phonological form of the word heard with all sorts of sensory-motor and functional properties of the entity denoted by that word. For example, infants come to learn that a /naı̈f/ (word heard) is a certain sharp and dangerous thing (shape and visual properties plus emotional connotation) that can make portions of food smaller (usefulness, pragmatic knowledge) but that they are not allowed to touch (normative rules). In this way, linguistic, conceptual and pragmatic items of information are contextually acquired by infants. This concomitance may explain why L1 lemmas have a more direct access or faster/solid link to/from conceptual knowledge than lemmas learned after the age of 5, which will simply be translated (coltello = knife) into the L1 entry to access semantic properties (parasitic association with the L1 lemma according to Bates and MacWhinney, 1989). Supporting data include, for example, a less demanding simultaneous interpreting (SI) condition toward the native (L2 > L1) than the foreign (L1 > L2) language for professional interpreters (Fabbro et al., 1990; Proverbio et al., 2004, 2007; Rinne et al., 2000).
Accordingly, it was shown in an ERP study (Proverbio et al., 2004) that professional Italian simultaneous interpreters who were highly proficient in English showed a difference in the amplitude of the N400 response to semantically incongruous terminal words only when the context was provided in L1 and the terminal word in L2 (mixed sentences), and under no other condition (unmixed or L2 > L1 sentences). Since the N400 component is known to reflect semantic integration processes (e.g., Federmeier et al., 2002), these data suggested that the difference in L1/L2 processing was not related to a difference in proficiency, but rather to a different functional organization of the L2 semantic integration system due to the later age of acquisition of L2 compared to L1.

Rinne et al. (2000) performed a PET study on Finnish/English simultaneous interpreters and found that SI into the non-native language (English) elicited much more extensive increases in left-sided fronto-temporal activation than SI into L1, which was interpreted as a sign that translation into the non-native language was more demanding that the opposite process.

According to the standard nativists, late learning is not as efficient as early learning because there is a critical period for language learning (Lenneberg, 1967), as for other biological functions. This hypothesis is supported by data concerning the difficulties in language learning encountered by children who have grown up in segregation, and by deaf children exposed to sign language at later ages. For instance, Newport (1990) observed that the ability to comprehend and produce inflected verb morphology in American Sign Language (ASL) decreases according to the age of first exposure to that language.

The role of language proficiency in bilinguals, which is very rarely equal for L1 and L2 languages, is controversial. Sometimes there are obvious differences in the proficiency and the age of language acquisition for unbalanced late bilinguals. In such cases it is not possible to draw any definitive conclusion about the neural hardware of bilingualism. Among the many examples, Yokoyama et al. (2006) very recently performed an fMRI investigation on language processing in late learners who were mid-proficiency Japanese/English bilinguals. They compared the processing of Japanese direct passive sentences with English passive sentences and found different activation patterns between L1 and L2. Rüschemeyer et al. (2006) compared fMRI activations in native German speakers with highly proficient Russian/German late-learner bilinguals during reading of German sentences containing a syntactic, a semantic, or no violation. L2 speakers demonstrated greater levels of activation than L1 speakers in several language processing areas including the left IFG, extending from the posterior IPS to the anterior IFG (BA45/47) and left MTG. In contrast, Perani et al. (1998) compared highly proficient Spanish/Catalan bilinguals with Italian/English late-learner bilinguals during story listening in L1 or L2. Their study revealed no effect of age of language acquisition on macroscopic brain activation. They concluded that when proficiency is kept constant, age of acquisition per se seems to have no impact on the linguistic representation of L2. However, it is possible that, in their study, the lack of difference between early and late learners was due to the non-demanding nature of the listening task.

But even with highly fluent bilinguals it is rare for L1 and L2 to be perfectly equivalent (Sebastian-Galles et al., 2006) and/or learned in the same socio/affective context. Sometimes L1 is learned precociously in a familiar context, but then is not used at school or for social or professional interactions. This determines a higher level of proficiency in L2 coupled with an earlier age of acquisition of L1. In other cases, L1 is learned and spoken for many years and then abandoned in favor of a new lexicon, as for immigrants or adopted children, which then becomes the exclusive language (e.g., Pallier et al., 2003). Even when bilinguals are apparently early and fluent in both languages, there are still observable differences between the languages and a certain preference for one of the two.

For example, Proverbio et al. (2002) presented Italian and Slovenian sentences (ending with either a congruent or an incongruent terminal word) to native fluent Slovenian/Italian bilinguals similarly educated in both languages. ERPs were recorded in these bilinguals and in balanced monolinguals (Italians). The data showed some differences in the amplitude and topography of major linguistic components as a function of language tested, including: (1) a less lateralized orthographic N170 to L2 than L1 words in bilinguals; (2) a less lateralized N400 component to semantically incongruous words in L2 than L1 words in bilinguals; (3) a lack of P600 component to syntactic violations in response to L2 sentences; and (4) a less lateralized P600 to L1 words compared to monolinguals.

One way to investigate language processing without confounding age of language acquisition with proficiency level is to study professional simultaneous interpreters, who can master multiple languages with the highest, and certified, proficiency level possible for a human speaker, along with a marked difference in the age of acquisition of maternal vs. foreign languages.

Unfortunately, to our knowledge, very few studies on multilingualism have been performed on professional simultaneous interpreters (e.g., Fabbro et al., 1990; Green et al., 1990; Proverbio et al., 2004; Rinne et al., 2000), and even fewer of them have performed brain measurements on such talented individuals.

In this study, we describe electrophysiological recordings on interpreters (about 40 years of age) who were native Italian speakers and had learned English (on average) after the age of 12. The aim was to disentangle the role of age of acquisition from that of fluency. We also observed their brain responses during processing of a third language (German) that had been acquired at the same age as English (late) but had been mastered with inferior proficiency (L3). This contrast allowed us also to investigate the effects of language proficiency on the timing of lexical processing. Words and pseudo-words were visually presented and the task consisted in responding to the presence of a given target letter (orthographic decision). As for the specific effect of word type and targetness on the amplitude of ERPs we expected an increase in the amplitude of occipito/temporal responses (N170 and later posterior components) for targets than non-targets, and for words than pseudo-words. It should be noted that some studies have shown an inverse relationship between word familiarity and the degree of activation of the visual word form area (localized in the left fusiform gyrus) with stronger BOLD signals for pseudo-words than words (Kronbichler et al., 2004; Mechelli et al., 2003). Consistently, some ERP studies (Hauk and Pulvermüller, 2004; Hauk et al., 2006) have shown lower ERP amplitudes elicited by words with high frequency compared with low frequency words (in the latency ranges 150–190 ms) in lexical decision tasks. This pattern of results has been interpreted as augmented brain activation for the processing of unfamiliar stimuli. The apparent inconsistency with the literature showing instead a direct relationship between VWFVA activation and the familiarity of words, has to do with the specific methodology, and in particular with task demands. Tasks involving an attentive selection of stimuli, that is, based on an orthographic decision task, are likely to elicit larger N1 and N2 components to target than non-target stimuli. As well known, target stimuli elicit an increase in posterior negativity (attention-related selection negativity) as compared to non-target stimuli; furthermore, the easier is the selection, the larger is the selection negativity.

Indeed, it has been shown (Flowers et al., 2004) that selective attention to letters increases the neurometabolic signal within the left extrastriate cortex (BA37). Several ERP studies involving a selective attention paradigm (and more precisely, an orthographic
decision task) reported increased N1 responses to orthographic than non-orthographic stimuli (Bentin et al., 1999), to familiar than non-familiar characters and to words than pseudo-words (Proverbio et al., 2006, 2007b). For the above reasons, we expected to find enhanced posterior responses to target than non-target strings, to words than pseudo-words, and possibly to native than foreign languages.

2. Methods

2.1. Participants

Seventeen highly specialized native Italian simultaneous interpreters participated in the present experiment. They were all female, from 28 to 53 years old (mean age 41.9 yrs; S.D.: 6.6), had right-handed manual preference as assessed by the Italian version of the Edinburgh Inventory (Salmasso and Longoni, 1985) and had a strong right-eye dominance (as attested by practical tests, such as looking inside a bottle or alternately closing each eye to evaluate parallax entity). Their mean lateral preference value (ranging from 1 to –1) was 0.93 (S.D. = 0.13). They were all graduates in Languages and Foreign Literature and specialized in conference interpreting. All had normal or corrected-to-normal vision and were in good health, and none had ever suffered from neurological or psychiatric disorders. Before participating in the experiment, all the interpreters were interviewed about a series of details that can be found in Table 1, including age, age and context of acquisition of L2 and L3 (English and German), professional activity present and past, and time exposed to each language in the period (about a month) immediately preceding the experimental session.

Participants were recruited according to professional use of L2 and L3 (simultaneous, consecutive, active or passive interpretation) and according to their credentials provided by professional associations.

2.2. Stimuli and procedure

Stimuli consisted of random sequences of isolated words and legal pseudo-words (390 words, 390 pseudo-words; a total number of 780 stimuli) presented one at a time at the center of a computer screen (see some examples of stimuli in Table 2). All strings were typed in Times font, and were white on a black background. The lengths of the words ranged from 4 to 7 cm. They were 1 cm in height and subtended visual angles of 0° 25’48” in the vertical axis and 1° 43’12” in the horizontal axis. Each block of 60 trials lasted about 1.5 min and was preceded by 3 warning signals “ready”, “set”, “go” presented for 250 ms. Each stimulus remained on the screen for 200 ms and was followed by a 1400–1600 ms random ISI. Subjects were instructed to stare at a fixed point located in the center of the screen.

Thirteen different characters were used as target letters through the different runs (see the Appendix for detail). At the beginning of each run, participants were informed of the target letter for the following run. In each run, half the stimuli were targets in that they included the target letter announced to subjects at the beginning of the trial. The task consisted of responding as accurately and quickly as possible to the presence of target letters by pressing a response key with the index finger of the left or right hand, taking no account of whether the word was congruous or non-existent. The two hands were used alternately during the recording session. The order of hand use and the task conditions were counterbalanced across subjects.

Each block of 60 trials consisted of a random sequence of 20 words for each language: Italian (IT), English (EN) and German (DE). For each sequence, there were 30 targets and 30 non-targets, 30 words (all nouns) and 30 pseudo-words (legal pseudo-words that were consistent with the specific orthography of each language). Stimuli were balanced in terms of imageability, frequency of use, length and position of target letter (beginning, middle or end of word).

2.3. EEG recording and analyses

The electroencephalogram (EEG) was continuously recorded from 30 scalp electrodes mounted in an elastic cap. Vertical eye movements were recorded by two electrodes placed below and above the right eye, and horizontal eye movements by electrodes placed at the outer canthi of the eyes. Linked ears served as the reference lead. The EEG and electrooculogram (EOG) were amplified with a half-amplitude band pass of 0.016–70 Hz. Electrode impedance was kept below 5 kΩ. Continuous EEG and EOG were digitized at a rate of 512 samples/s. EEG epochs were synchronized with the onset of stimulus presentation.

Computerized rejection of electrical artifacts was performed before averaging to discard epochs in which eye movements, blinks, excessive muscle potentials or amplifier blocking occurred. The artifact rejection criterion was a peak-to-peak amplitude exceeding 50 μV, and the rejection rate was ~5%. ERPs were averaged offline from 100 ms before stimulus onset. For each subject, distinct ERP averages were obtained according to stimulus category. ERP components were identified and measured with reference to the average baseline voltage over the interval from –100 to 0 ms relative to stimulus onset.

Table 1

<table>
<thead>
<tr>
<th>Part</th>
<th>Age</th>
<th>L2: age of acquisition</th>
<th>L2: professional use</th>
<th>L3: age of acquisition</th>
<th>L3: exposure</th>
<th>L3: professional use</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>Other languages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28</td>
<td>15</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>15</td>
<td></td>
<td></td>
<td>533</td>
<td>590</td>
<td>558</td>
<td>French,Spanish</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>7</td>
<td>Daily EN&lt;-&gt;IT</td>
<td>Uncertain</td>
<td></td>
<td>Unofficially,</td>
<td>533</td>
<td>547</td>
<td>537</td>
<td>French</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>8</td>
<td>Daily EN&lt;-&gt;IT</td>
<td>13</td>
<td>120</td>
<td>Simultaneous DE &gt; IT</td>
<td>588</td>
<td>592</td>
<td>601</td>
<td>French</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>11</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>14</td>
<td>–</td>
<td>Translation</td>
<td>584</td>
<td>602</td>
<td>579</td>
<td>French</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>19</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>11</td>
<td>2</td>
<td>Negotiation</td>
<td>550</td>
<td>577</td>
<td>555</td>
<td>Spanish</td>
</tr>
<tr>
<td>6</td>
<td>41</td>
<td>13</td>
<td>Consecutive, negotiation EN &gt; IT</td>
<td>17</td>
<td>30</td>
<td>Negotiation and consecutive DE &gt; IT</td>
<td>664</td>
<td>683</td>
<td>662</td>
<td>French</td>
</tr>
<tr>
<td>7*</td>
<td>42</td>
<td>11</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>Uncertain</td>
<td></td>
<td></td>
<td>560</td>
<td>580</td>
<td>556</td>
<td>French</td>
</tr>
<tr>
<td>8</td>
<td>42</td>
<td>11</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>Uncertain</td>
<td></td>
<td></td>
<td>614</td>
<td>607</td>
<td>617</td>
<td>French</td>
</tr>
<tr>
<td>9</td>
<td>42</td>
<td>13</td>
<td>Daily EN&lt;-&gt;IT</td>
<td>13</td>
<td>Rare</td>
<td>Rarely,</td>
<td>530</td>
<td>579</td>
<td>550</td>
<td>Russian</td>
</tr>
<tr>
<td>10</td>
<td>42</td>
<td>9</td>
<td>Consecutive, negotiation EN&lt;-&gt;IT</td>
<td>14</td>
<td></td>
<td>Simultaneous DE&lt;-&gt;IT</td>
<td>521</td>
<td>579</td>
<td>540</td>
<td>French</td>
</tr>
<tr>
<td>11</td>
<td>42</td>
<td>20</td>
<td>Simultaneous EN &gt; IT</td>
<td>17</td>
<td>5</td>
<td>Rarely,</td>
<td>511</td>
<td>524</td>
<td>512</td>
<td>French</td>
</tr>
<tr>
<td>12*</td>
<td>46</td>
<td>20</td>
<td>Daily EN&lt;-&gt;IT</td>
<td>19</td>
<td></td>
<td>Rarely,</td>
<td>571</td>
<td>576</td>
<td>583</td>
<td>French</td>
</tr>
<tr>
<td>13</td>
<td>46</td>
<td>5</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>33</td>
<td></td>
<td>Consecutive</td>
<td>551</td>
<td>560</td>
<td>554</td>
<td>French</td>
</tr>
<tr>
<td>14</td>
<td>47</td>
<td>13</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>Uncertain</td>
<td></td>
<td></td>
<td>529</td>
<td>562</td>
<td>554</td>
<td>French</td>
</tr>
<tr>
<td>15</td>
<td>48</td>
<td>3</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>15</td>
<td>220</td>
<td>Simultaneous DE&lt;-&gt;IT</td>
<td>518</td>
<td>547</td>
<td>521</td>
<td>French</td>
</tr>
<tr>
<td>16</td>
<td>50</td>
<td>11</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>8</td>
<td></td>
<td></td>
<td>593</td>
<td>625</td>
<td>594</td>
<td>French</td>
</tr>
<tr>
<td>17</td>
<td>53</td>
<td>18</td>
<td>Simultaneous EN&lt;-&gt;IT</td>
<td>7</td>
<td></td>
<td></td>
<td>626</td>
<td>636</td>
<td>635</td>
<td>French</td>
</tr>
<tr>
<td>Mean</td>
<td>41.9</td>
<td>12.2</td>
<td>Mean</td>
<td>96</td>
<td>15</td>
<td>Mean</td>
<td>563</td>
<td>586</td>
<td>571</td>
<td>French</td>
</tr>
</tbody>
</table>

Interpreters 7 and 12 were subsequently discarded for excessive EEG artifacts. ‘Exposure’ refers to the active exposure (interpreting and teaching) to spoken language in the last month (in hours per month). Passive exposure (reading, listening) was much higher for all interpreters. A low number of hours indicate that, in the previous month, the interpreters had been using a different language in their professional activity (French, Spanish, Danish or Russian). Reaction times are referred to target words.
Table 2
Examples of some of the stimuli presented during a session in which the target was the letter N

<table>
<thead>
<tr>
<th>Word type</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT W targets</td>
<td>ATENEO</td>
<td>PENITTO</td>
<td>INCISORE</td>
<td>ELENESMO</td>
<td>QUOTAZIONE</td>
</tr>
<tr>
<td>IT W non-targets</td>
<td>ABISSO</td>
<td>SCALIE</td>
<td>SCIATORE</td>
<td>IDOLATRIA</td>
<td>CAPOTATO</td>
</tr>
<tr>
<td>IT PS targets</td>
<td>NAGLIO</td>
<td>TUCELNA</td>
<td>NERIFACIO</td>
<td>GIONASCO</td>
<td>GIUSASTENO</td>
</tr>
<tr>
<td>IT PS non-targets</td>
<td>ERUSTE</td>
<td>SEQUIBA</td>
<td>ASURDITA</td>
<td>QUASIRIVO</td>
<td>FRUBIGOSTO</td>
</tr>
<tr>
<td>EN W targets</td>
<td>KNIGHT</td>
<td>MISSION</td>
<td>LIGHTING</td>
<td>BREAKDOWN</td>
<td>SCRUBWOMAN</td>
</tr>
<tr>
<td>EN W non-targets</td>
<td>RIDOLE</td>
<td>THOUGHT</td>
<td>HAULAWAY</td>
<td>EXPOSITOR</td>
<td>CROSSBREAD</td>
</tr>
<tr>
<td>EN PS targets</td>
<td>TRAWSNS</td>
<td>TREANCH</td>
<td>SPOUNGER</td>
<td>ENWEGETHER</td>
<td>FEERSONPOW</td>
</tr>
<tr>
<td>EN PS non-targets</td>
<td>CHITCH</td>
<td>SCREEVE</td>
<td>SCROWSET</td>
<td>MERITOGLE</td>
<td>FURSOUGHTY</td>
</tr>
<tr>
<td>GE W targets</td>
<td>GELEMM</td>
<td>ACHTUNG</td>
<td>NOTHILFE</td>
<td>EINTRACHT</td>
<td>STEINKOHLE</td>
</tr>
<tr>
<td>GE W non-targets</td>
<td>WURFEL</td>
<td>STOPEL</td>
<td>FAULHEIT</td>
<td>BESCHLUSS</td>
<td>VOLKERMORD</td>
</tr>
<tr>
<td>GE PS targets</td>
<td>GENOURT</td>
<td>NARTSCH</td>
<td>FELMINEM</td>
<td>HUPGREUNT</td>
<td>NOCKMEZOL</td>
</tr>
<tr>
<td>GE PS non-targets</td>
<td>SCHMOR</td>
<td>FERSCH</td>
<td>SCHASTIC</td>
<td>GAUDRUEHE</td>
<td>BLITZGRAUSE</td>
</tr>
</tbody>
</table>

N1 peak latency and amplitude values were measured at inion (IN3, IN4) and lateral occipital (OL, OR) scalp sites within the 160–180 ms time window. Mean area values of posterior N2 and N3 and posterior P300 components were measured at inion (IN3, IN4), lateral occipital (OL, OR) and posterior temporal (T5 and T6) sites in the time windows 260–320, 320–380 and 400–600 ms, respectively. At anterior sites, the mean area values of the frontal N1 and N2 components were measured at central (C3, C4) and frontal (F3, F4) sites between 175–220 and 220–290 ms, respectively. At the same sites, lexical processing negativity (LPN) and late positivity (LP) were measured in the time windows 290–390 and 400–600 ms, respectively.

3. Results

3.1. Electrophysiological data

3.1.1. Occipital/temporal area

3.1.1.1. N1 response (160–180 ms).

Electrode: N2 was largest over the inion area (IN = −2.69; OCL = −0.46; T = −0.21 μV). Hemisphere: it also exhibited a hemispheric asymmetry, being larger over the left (LH = −1.97 μV) than the right hemisphere (RH = −0.28 μV). Language: lexical factors affected N2 response, with larger amplitudes to IT (L1) and EN (L2) than DE stimuli. Language × Electrode: this interaction showed anatomical specificity for the language effect, dissociated from the region of maximum amplitude (IN3IN4): IT = −2.925; EN = −2.71; DE = −2.44; OL/OR: IT = −0.93; EN = −0.48; DE = 0.03; T5/T6: IT = −0.53; EN = −0.27; DE = 0.17 μV). Post hoc comparisons showed significant differences between both L1 and L2 stimuli (p < 0.001) and L2 and L3 stimuli (p < 0.001) at lateral occipital sites, and significant L1 vs. L3 differences at all sites (p < 0.001).

Fig. 4 shows the scalp topographic distribution of difference waves obtained by subtracting ERPs to L2 from ERPs to L1 stimuli (upper row), and ERPs to L3 from ERPs to L2 stimuli (lower row). Maps were computed for the time window corresponding to the N2 peak. A strong effect of age of acquisition is visible, resulting from the IT/EN contrast over the left tempo-parietal area, and a smaller but reliable effect of proficiency resulting from the EN/DE contrast over the left lateral occipital area.

3.1.1.2. N2 response (260–320 ms). Electrode: N2 was largest over the inion area (IN = −2.69; OCL = −0.46; T = −0.21 μV). Hemisphere: it also exhibited a hemispheric asymmetry, being larger over the left (LH = −1.97 μV) than the right hemisphere (RH = −0.28 μV). Language: lexical factors affected N2 response, with larger amplitudes to IT (L1) and EN (L2) than DE stimuli. Language × Electrode: this interaction showed a significant difference in word vs. pseudo-word processing (p < 0.005) only at left hemispheric sites, with larger N2 responses to real words than pseudo-words (LH: Words = −2.21; Pseudo-words = −1.71; RH: Words = −0.31; Pseudo-words = −0.25 μV). Targetness × Hemisphere: again, hemispheric asymmetry was observable in the effect of letter targetness, as proved by the significant interaction target/non-target differences (p < 0.05) only at left hemispheric sites (LH: T = −2.24; NT = −1.68; RH: T = −0.23; NT = −0.33 μV). In summary, this component was larger over the left inion area but lexical effects were mostly visible at the left lateral occipital site. N2 was larger to targets than non-targets, to words than pseudo-words, to L1 than L2, and to L2 than L3 items.

3.1.1.3. N3 response (320–380 ms). Electrode: like the N2 response, N3 showed greater amplitude over the inion area as proved post hoc comparisons (IN = −3.285; OCL = −1.96; T = −1.09 μV). Language: N3 was highly sensitive to stimulus language, showing greater activation to L1 and L2 than to L3 stimuli (p < 0.005). Language × Electrode: again, as for the N2 response, a significant interaction was found. Post hoc comparisons showed a significant L1 vs. L2 and L2 vs. L3 difference at lateral occipital sites (OL/OR: IT = −2.48; EN = −2.09; DE = −1.29; OL/OR: IT vs. EN: p < 0.01; EN vs. DE: p < 0.01; IT vs. DE: p < 0.001), no L1 vs. L2 difference at other sites and a significant L2 vs. L3 and L1 vs. L3 difference at posterior temporal sites (T5/T6: IT vs. EN: n.s.; EN vs. DE:
Fig. 1. Grand-average ERPs elicited by Italian, English and German words, irrespective of lexical category, and recorded at left and right inion (IN3, IN4), lateral occipital (OL, OR), parietal (P3, P4) and frontal (F3, F4) sites.

3.1.1.4. P3 response (400–600 ms). Electrode: posterior P3 was significantly larger at posterior/temporal sites (IN = −1.37; OCL = −0.29; T = 0.68 μV). Targetness: at this latency range P3 was greater for target than non-target. Targetness × Hemisphere: this interaction evidenced that P3 to targets was largest over right hemispheric sites (LH: Target = −0.13; Non-target = −0.97 (p < 0.005); RH, Target = 0.93; Non-target = −1.13 μV (p < 0.001)). Targetness × Electrode: the increase in positivity to targets was largest at posterior-temporal sites. Language × Targetness: this interaction demonstrated a greater target selection effect for L1 than L2 or L3 (IT: T = 0.84; NT = −1.38; EN: T = −0.07; NT = −1.05; DE: T = 0.42; NT = −0.72 μV).

Language × Hemisphere: P3 was more sensitive to stimulus language over the left than the right hemisphere as proved by post hoc comparisons (LH: L1 vs. L2 (p < 0.005); L2 vs. L3 (p < 0.05); RH: n.s.). Word type and Word type × Hemisphere: at this latency stage the evoked response was still more negative to words than pseudo-words, especially over the left hemisphere. Word type × Targetness: the word type effect was stronger for non-targets (Words = −1.48; Pseudo-words = −0.62 μV) than targets (Words = 0.35; Pseudo-
words = 0.44 μV), consistent with previous data (Proverbio et al., 2006).

3.1.2. Fronto/central areas

3.1.2.1. N1 response (175–220 ms). Language: anterior N1 was larger for L1 than L3 stimuli. Language × Targetness × Electrode: this interaction showed a target effect only for L1 stimuli at frontal sites (F3/F4: IT T vs. NT < 0.001; target = 3.61; non-target = 3.035). This is the first effect of age of acquisition at frontal sites. Targetness × Hemisphere: at this latency, N1 was already more positive to targets than non-targets over the right hemisphere. This result probably reflects overlapping with the rising phase of the P3 component (LH: T = 3.10; NT = 2.94; RH: T = 3.28; NT = 2.84 μV).

Word type × Targetness × Electrode: the first word-type effect resulted from this interaction, showing a more negative N1 to pseudo-words than words (when targets) at both frontal (Words = 4.23; Pseudo-words = 3.78 μV) and central (Words = 2.64; Pseudo-words = 2.12 μV) sites. In summary, anterior N1 showed a targetness effect only for the native language, was much larger to L1 than L3 stimuli, evidencing an additional effect of proficiency, and was more negative to pseudo-words than words.

3.1.2.2. N2 response (220–290 ms). Language: the anterior N2 response was larger (p < 0.001) to L1 than L2 stimuli, and to L2 than L3 stimuli. Language × Word type × Electrode: this interaction showed a word type effect only for L1 stimuli at frontal sites (IT Words = 3.50; IT Pseudo-words = 2.54; EN Words = 3.33; EN Pseudo-words = 3.63; DE Words = 3.79; DE Pseudo-words = 3.74 μV). Post hoc comparisons showed a significant word/pseudo-word difference only for L1 at frontal sites (p < 0.001). N2 to words was larger for L1 and L2 than for the less proficient L3 at central sites (p < 0.001) whereas no difference was found between the responses to the equally proficient L1 and L2. To summarize, the age of acquisition effect was evidenced by the lexical factor (word/pseudo-word contrast), whereas proficiency was evidenced by the response to words.

At both central and frontal sites, N2 to pseudo-words differed for native and foreign languages, with significant differences between L1 and L2 (p < 0.001) and L1 and L3 (p < 0.001) strings, but there were no statistically significant differences between L2 and L3 strings.

Targetness and Targetness × Electrode: these interactions evidenced a larger N2 to target than non-target stimuli, particularly at frontal sites.

Word type × Hemisphere: this interaction demonstrated a larger lexical effect at left sites (LH: Words = 2.72; Pseudo-words = 2.43 (p < 0.001); RH: Words = 3.33; Pseudo-words = 3.20 μV). Word type × Targetness × Electrode: As for anterior N1, the significant interaction showed a larger negativity to pseudo-words than words only when they were targets, especially at central sites. To summarize, anterior N2 was still very negative to pseudo-words.
Fig. 3. Grand-average ERPs elicited by words and pseudo-words of the 3 languages (IT, EN, DE) and recorded at left and right lateral occipital sites.

Fig. 4. Topographic difference maps obtained by plotting color-coded values of difference voltage recorded in response to L2 from ERPs to L1 stimuli (upper row), and ERPs to L3 from ERPs to L2 stimuli (lower row), in the latency range corresponding to the peak of the N2 component.
than words, to targets than non-targets and evidenced both the effect of age of language acquisition and proficiency.

3.1.2.3. Lexical processing negativity, LPN (290–390 ms). Language: this wide negative deflection evidenced significant differences between L1 and L2 ($p < 0.005$), L1 and L3 ($p < 0.001$), and L2 and L3 ($p < 0.05$) stimuli. Word type: LPN was much larger for pseudo-words than words. Language x Word type: this interaction revealed a much larger LPN difference (words vs. pseudo-words) in L1 (IT Words = 3.02; IT Pseudo-words = 1.27 ($p < 0.01$) than in L2 or L3 (EN Words = 3.28; EN Pseudo-words = 2.69; DE Words = 3.90; DE Pseudo-words = 3.58 μV). ERP waveforms recorded at left and right frontal areas as a function of language and word type are displayed in Fig. 6, which shows marked effects of both factors alone and in interaction with each other. Furthermore, LPN was of equal amplitude to words in the 3 languages (thus proving that the interpreters had a certain level of proficiency in all languages), whereas significant differences arose

![Fig. 5. Mean amplitudes (μV) of occipito/temporal N1, N2 and N3 responses to words belonging to the various languages.](image)

![Fig. 6. Grand-average ERPs recorded at left and right frontal areas as a function of language and word type.](image)
in the response to pseudo-words as a function of their orthographic appearance: (IT Pseudo-words vs. EN Pseudo-words $p < 0.001$; IT Pseudo-words vs. DE Pseudo-words $p < 0.001$; EN Pseudo-words vs. DE Pseudo-words n.s.), as displayed in Fig. 6.

Language × Word type × Electrode: this interaction showed that the word/pseudo-word difference was significant for both L1 and L2 strings at frontal sites. It showed also a significant difference between LPN to L2 vs. L3 words (proficiency effect) especially at frontal sites (EN Pseudo-words = 3.08; DE Pseudo-words = 4.02 $\mu$V). The effect of language proficiency was mostly evident in the lack of word/pseudo-word effect for L3 in the amplitude of LPN.

Targetness: owing to temporal overlaps with the task-related P3 response, LPN was more positive to targets than non-targets. Targetness × Electrode: this effect was particularly striking at frontal sites as suggested by post hoc comparisons for this interaction (C3\C4: $T = 2.79$; NT = 2.19; F3\F4: $T = 4.21$; NT = 2.65 $\mu$V; post hoc C3\C4 T vs. NT $p < 0.001$; F3\F4 T vs. NT $p < 0.001$). Targetness × Hemisphere: this significance showed larger target/non-target differences over right hemispheric sites (LH: Target = 2.99; Non-target = 2.33; RH: Target = 4.00; Non-target = 2.51 $\mu$V). In summary, while frontal LPN was equally larger to words in the 3 languages, it was markedly affected by the age of acquisition and proficiency showing a clear gradient in the response to pseudo-words.

3.1.2.4. Late positivity, LP (400–600 ms). Word type: LP was more positive to words than pseudo-words. Language × Word type: this interaction revealed a larger word/pseudo-word difference in the native compared to foreign languages, as evidenced in Fig. 7, Top. LP was very sensitive to the different orthographic appearance of pseudo-words. Post hoc comparisons showed a significant difference between L1 and L3 pseudo-words ($p < 0.005$). Language × Word type × Electrode: the interaction evidenced a significant lexical effect (word/pseudo-word, $p < 0.01$) only for L1 and L2 (thus suggesting an effect of proficiency) especially at frontal sites (C3\C4: L1 Words = 6.57; Pseudo-words = 4.49; L2 Words = 6.15; Pseudo-words = 5.28; L3 Words = 6.59; Pseudo-words = 5.98; F3\F4: L1 Words = 6.98; Pseudo-words = 4.03; L2 Words = 6.33; Pseudo-words = 5.11; L3 Words = 6.07; Pseudo-words = 5.85 $\mu$V).

Overall, LP was greater for L1 than L3 words ($p < 0.005$) at frontal sites. Over the same area, LP differed more consistently as a function of the orthographic appearance of pseudo-words, leading to the further significance of L2 vs. L3 comparisons ($p < 0.05$).

Targetness: as for LPN, the LP complex was much more positive to targets (6.58 $\mu$V) than non-targets (4.99 $\mu$V), as evidenced by the “targetness” factor. Targetness × Hemisphere: this interaction proved a larger target/non-target difference over the right hemisphere. Language × Targetness: this factor suggested an effect of language orthography rather than proficiency in the letter detection task (IT: $T = 6.77$; NT = 4.26; EN: $T = 6.16$; NT = 5.27; DE: $T = 6.82$; NT = 5.43 $\mu$V); indeed, post hoc comparisons evidenced a significant target/non-target difference only for languages with a transparent orthography, namely: IT ($p < 0.001$) and DE ($p < 0.05$), but not EN (see Fig. 7, Middle).

Word type × Targetness × Hemisphere: the triple interaction, evidenced a larger lexical effect for target than non-target stimuli, especially at right hemispheric sites (LH Target: Words = 6.69; Pseudo-words = 5.19; LH Non-target: Words = 5.61; Pseudo-words = 4.42; RH Target: Words = 8.11; Pseudo-words = 6.35; RH Non-target: Words = 5.38; Pseudo-words = 4.54 $\mu$V). Overall, LP deflection exhibited a larger word/pseudo-word difference for the

![Fig. 7](image-url) (Top) Linguistic proficiency. Mean values of LP complex (300–500 ms) as a function of language and lexical type. This contrast clearly shows the effect of language proficiency. (Middle) Shallow vs. deep orthography. Amplitude values of LP complex (300–500 ms) as a function of language and stimulus targetness. This contrast indicates the effect of orthographic regularity and depth in the letter search task, and shows a cost (in terms of smaller LP and targetness effect, indicated by the arrow) for English vs. the more transparent German and Italian languages. (Bottom) Reaction times (ms) as a function of language and lexical type. This contrast clearly shows the effect of orthographic regularity and depth in the letter search task, and shows a cost (in terms of smaller LP and targetness effect, indicated by the arrow) for English vs. the more transparent German and Italian languages.
earlier acquired (L1 vs. L2) and more proficient (L2 vs. L3) languages. On the other hand, the target/non-target difference was greater for shallow than deep orthographies.

3.2. Behavioral data

Language: the analysis of RTs showed the significance of the language factor, with faster responses to strings characterized by a shallow orthography (IT and DE) compared to strings with a deep orthography (EN), as proved by post hoc comparisons (IT = 563; EN = 587; DE = 571 ms; IT vs. EN p < 0.001; IT vs. DE n.s.; EN vs. DE p < 0.001). Word type: this factor was also significant, showing faster RTs to words than pseudo-words (Words = 566; Pseudo-words = 581 ms.). The interaction “word type x language” bordered on significance (p = 0.07) with smaller lexical effects for foreign than native languages (see Fig. 7, Bottom). To summarize, response speed to target letters was greater for words (than pseudo-words) and transparent (than opaque) orthographies.

4. Discussion

In this paper, the time course and scalp topography of brain activation were investigated during linguistic processing of native vs. foreign languages mastered equally (L2) or less (L3) proficiently than L1, in professional Italian simultaneous interpreters. The data showed marked differences in the temporal course of linguistic processes such as recognition of orthographic appearance, letter identification and lexical access for native vs. foreign languages (L1 vs. L2 and L3) and deeply mastered vs. not mastered (L2 vs. L3) languages. The ERP data showed clear markers of age of acquisition and language proficiency. Particularly relevant is the clear-cut difference between native and foreign languages (proficiency being equal) in this silent reading task not requiring semantic processing. Despite the putative comparability in proficiency of Italian vs. English for these experienced and highly skilled professionals, L1 was the only language that showed early lexical effects (distinction of words from pseudo-words) at occipito-temporal sites as early as 160–180 ms. L2 words were distinguished from pseudo-words for the first time at about 260–320 ms (N2 level), while L3 words showed a lexical effect only at about 320–380 ms (N3 level) at posterior sites. Again, only L1 evidenced the presence of lexical effects, as early as 175–220 ms, at fronto-central sites. They were observable much later (at about 220–290 ms) for L2 items, and never fully observable for German words at frontal sites.

The finding of early semantic effects (<200 ms) for single word processing in the ERP literature is fairly well confirmed (Assadollahi and Pulvermüller, 2001, 2003; Martin-Loeches et al., 2004; Hauk et al., 2006; Hauk and Pulvermüller, 2004; Penolazzi et al., 2007; Proverbio et al., 2004; Pulvermüller et al., 2001; Sereno et al., 1998). For example, Sereno et al. (1998) reported a differential response to words vs. pseudo-words as early as 112 ms post-stimulus. Proverbio et al. (2004) showed a left centro-parietal P140 larger to high-frequency than low-frequency words, and to words and pseudo-words than to non-letter strings, thus suggesting an early recognition of word familiarity. Penolazzi et al. (2007) found early lexical effects, modulated by word length, as early as 120 ms. Assadollahi and Pulvermüller (2003) found early effects of word frequency at about 120–170 ms for short monosyllabic words, and later effects of word frequency (240–270 ms) irrespective of word length. These data suggest that the often-reported later lexical effects might be related to the lengthy processing of longer and less familiar words, as well as to methodological factors such as differences in word length, word class, repetition rate, word frequency, display duration, task type etc., as suggested, for example, by Martin et al. (2006).

The fact that only L1 words were discriminated from pseudo-words at the earliest processing stage suggests a faster or more solid access to word properties for the native language than for languages learned later in life, regardless of proficiency.

The effect of age of acquisition was also evidenced by a greater left occipito-temporal N2 to L1 than L2 words, as well as to L2 than L3 words (proficiency).

Owing to the obvious lack in spatial resolution of the ERP technique, we will not discuss differences in brain topography as a function of age of acquisition or proficiency. However, the parieto/temporal activation for processing of L1 vs. L2 (languages learned earlier vs. later, proficiency being equal) observed at about 260–320 ms in posterior brain areas may deserve some attention. This activation might be conceived as indicating a stronger involvement of areas linked to conceptual knowledge for automatic access to L1 meaning. On the other hand, the greater occipital activation for the L2 vs. L3 contrast (languages mastered with different levels of proficiency, age of acquisition being similar) might indicate an effect of orthographic familiarity for L2 as opposed to L3 strings. However, this hypothesis deserves further investigation and is offered here as a speculation.

The targetness effect, that is the modulation in ERP amplitude related to letter search and attentive selection, affected the amplitude of N2 (260–320 ms), with larger selection latencies at occipito/temporal sites for target strings in all languages. The interaction “Targetness x Hemisphere” also proved very significant at the N3 level at posterior brain sites, again with no difference in letter search or selection as a function of age of language acquisition or proficiency at this stage and electrode site. This effect might indicate the activity of neural populations devoted to orthographic processing, characterized by a small receptive field and low lexical sensitivity.

Both ERP and neuroimaging studies have proved that letter searches engage, in part, the neural network normally involved in orthographic analysis. For example, Proverbio et al. (2007b) showed specific activation of the left fusiform gyrus (BA37) at both the N1 and N2 levels, as shown by the difference wave obtained by subtracting ERPs to non-targets from ERPs to target letters in a similar task, using LORETA inverse solution computations. Again, the fMRI study by Flowers et al. (2004) showed that attending to letters was associated with enhanced activity in a portion of the left extrastriate cortex identified in Brodmann’s Area 37, and possibly corresponding to the Visual Word Form Area.

At occipito/temporal sites, but at later processing stages (400–600 ms), P3 proved to be affected by the age of language acquisition in target identification, being greater for L1 than for L2 or L3 targets, and over the right hemisphere.

At anterior brain areas the N1 response (175–220 ms) evidenced a significant interaction among the language x targetness x electrode factors, proving that selection occurs early only for L1 stimuli at frontal sites. This was the earliest effect of age of acquisition at frontal regions, especially over the right hemisphere. Anterior N2 (220–290) proved to be larger for target than non-target stimuli, irrespective of language. Both the LPN (290–390) and LP (400–600 ms) complexes were much more positive for targets than non-targets particularly at right hemispheric sites. Between 220 and 390 ms, targetness was not particularly affected by lexical factors.

At the LP level (400–600 ms), the Language x Targetness interaction suggested an effect of language orthography (rather than proficiency) in the letter detection task. Indeed, statistical comparisons evidenced a significant target/non-target difference only for languages with a shallow orthography, namely Italian (p < 0.001) and German (p < 0.05), but not English (see Fig. 7, Middle), which is characterized by a deep orthography. This datum strongly correlates with the pattern of behavioral data (RTs).
showing, overall, slower RTs to English than the other languages (see Fig. 7, Bottom). Overall, the effect of orthographic depth of the language affected late processing stages relatively independent of age of acquisition or proficiency.

The present data also provide evidence that the native language of a silent person may be inferred from the electrical brain activity evoked by exposure to linguistic material to be attentively examined but not explicitly comprehended. Without suggesting the possibility of mind reading (very dangerously approaching serious privacy matters), the present findings are nevertheless quite interesting since other methods for identifying the nationality of an individual on the basis of overt linguistic testing (analysis of accent or pronunciation, vocabulary, knowledge of geographical or cultural facts) are considered to be far from valid or reliable (e.g., Eades et al., 2003).

The lack of difference in LPN in response to words of the three languages is very similar to previous findings on a different group of interpreters (Proverbio et al., 2004) engaged in a semantic decision task. In that experiment, interpreters were presented with 400 short sentences, half of which had an unexpected final word, producing a semantic incongruity. Sentences could be entirely in Italian or in English (unmixed); alternatively, the body of the sentence could be in English and the final word in Italian or vice versa (mixed). ERPs were time-locked to the onset of the final word. At the N400 level, ERPs were significantly larger to L2 than to L1 words only in the mixed and not in the unmixed condition. No effect of language was observed in the unmixed condition, suggesting that the difference in L1/L2 processing was not related to a difference in proficiency, but rather to a different functional organization of semantic integration systems due to the later age of acquisition of L2 compared to L1.

No differences in hemispheric asymmetry were found as a function of language. These data suggest that the reduced left lateralization of linguistic functions shown by several electro-physiological (Proverbio et al., 2002, 2006) and neuroimaging studies in bilinguals is specific for semantic processing that requires access to conceptual knowledge.

As for the earliness of lexical effects on the amplitude of ERP components, our data indicated early semantic modulation (word/pseudo-word difference) at posterior N170 in the form of larger evoked responses to familiar than non-existent lexemes only for L1 stimuli. It is interesting to note that other studies have shown a similar relationship (the greater the familiarity, the higher the activation) between word familiarity and degree of activation of left occipito-temporal regions. For example, some literature shows the presence of a larger N1 to alphabetic than to non-alphabetic characters (e.g., Bentin et al., 1999; Maurer et al., 2005) during explicit reading tasks, whereas other studies have shown a greater activation of VWFA, as reflected by an increase in M170 response, to letters compared to icons in normal individuals, and a lack of it in dyslexic readers (Helenius et al., 1999; Salmelin et al., 1996). On the other hand other studies have shown an opposite pattern of results: for example, Proverbio et al. (2007b) showed an enhanced occipito/temporal N170 response to mirror than standard words during a similar letter detection task. However, LORETA source modeling revealed that the intracranial source corresponding to that effect (that is, N1 to mirror minus standard words) was localized in the right occipital lobe (BA 18), which does not correspond to the left-lateralized VWFA, therefore, suggesting a different aspect of object processing.

The present data also showed larger N1 responses (both posterior and anterior) to native than to foreign languages in which proficiency was comparable (excellent), thus suggesting the presence of early latency mechanisms supporting automatic access to the lexicon driven by the orthographic appearance of the stimulus.

Acknowledgments

This study was funded by FAR 2006 and PRIN200319330.003 grants to AMP, and CNR grants to AZ. We are very grateful to Marzia Del Zotto and Valentina Rossi for their kind technical support. We are also indebted to Marco Perugini and Marcello Gallucci for statistical advice, and to Dennis Molfese for his helpful and constructive comments.

References


A.M. Proverbio et al. / Biological Psychology 80 (2009) 52–63