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Language selection in bilinguals: A spatio-temporal analysis of electric brain activity

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Abstract

Language selection refers to the cognitive mechanism that allows bilinguals to communicate in one language or the other and to switch between languages depending on the listener. Previous studies suggested that various brain areas might be involved in this process. However, the question remains whether language selection is achieved through a language-specific mechanism or through a general cognitive control process. To address this question, we compared event-related potentials (ERPs) induced by language selection and task selection processes during image naming. ERPs were collected from bilingual subjects while tested in two different contexts: a monolingual task selection context (TSc) where a post-stimulus cue instructed subjects either to name the image or generate a corresponding verb in their first language (L1), and a bilingual language selection context (LSc) where the cue indicated to name the image either in the first or the second language. By comparing the ERPs induced by the same L1 naming as a function of context, we assumed that if the selection processes varied across contexts, then electric brain responses should differ rapidly after the cue presentation. Our analysis indicated that the first ERP differences accounting for the diverging processes involved appeared between ~220 and 300 ms after the cue. The estimation by source localisation of brain regions accounting for these differences pointed to an increased activation during LSc in the left middle frontal–precentral gyri, supramarginal and angular gyri. Our results suggest that language selection is achieved through a neural network involving areas implicated in both general cognitive processes and language processing.

Keywords: Event-related potentials; Temporal segmentation; Source localisation; Task selection; Functional microstates; Cognitive control; Overt naming, First language; Second language

1. Introduction

Language representation in the bilingual brain has been the subject of great interest in cognitive neuroscience and much of the research has focused on the cerebral representation of the first (L1) and the second learned language (L2). Cognitive models tend to assume the existence of a single conceptual representation for the two languages, which is linked to two different lexical representations (Kroll and Stewart, 1994; Francis, 1999; Gollan and Kroll, 2001). In parallel, functional imaging studies investigating language functions (*i.e.* production and comprehension) support the existence of a largely common cerebral network for the different languages, whose activation is mainly modulated by the level of proficiency and age of acquisition of L2 (Perani et al., 1998; Chee et al., 1999; Price et al., 1999; Wartenburger et al., 2003; Perani and Abutalebi, 2005). Controversy however remains on the nature

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Abbreviations: ERP, event-related potentials; L1, first language; L2, second language; TSc, task selection context; LSc, language selection context.

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of the cognitive processes engaged during the selection of lexical items from L1 or L2 during language production.

Behavioural studies have often addressed the issue of lexical retrieval in terms of competition processes (*e.g.* Kroll and Peck, 1998; Costa and Caramazza, 1999; Colomé, 2001; Lee and Williams, 2001). Following one line of argumentation, bilinguals must actively select a target language (*i.e.* the language in which the speaker is asked to communicate) and simultaneously inhibit (Green, 1998) or raise the activation threshold of the non-target language (Grosjean, 2001). This latter view assumes that both languages can remain active (*e.g.* as a function of the speaker's preferred language) during speech production as suggested by the frequent occurrence of unwanted L1 interferences during the use of a weaker L2 (Grainger and Dijkstra, 1992; Grosjean, 1992; Grainger, 1993).

Although the idea of competition between (or active selection of) languages is not universally accepted (Costa and Caramazza, 1999; Roelofs, 2003), the study of the recovery patterns in bilingual aphasics tends to support such a view. According to Green (2003), the selective recovery of one language in bilingual aphasia (while the other remains impaired or lost) and the pathological mixing (or switching) of languages can both be explained in terms of dysfunction of a so-called language selection mechanism. In the former case, the damage would permanently inhibit the non-recovered language while in the latter case the damage would result in an uncontrolled and often erroneous selection of a target language. From a neurological perspective, it has been observed that either the pathological fixation to one language (*i.e.* selective recovery, Aglioti and Fabbro, 1993) or the uncontrolled switching between languages may occur after lesions to the left prefrontal cortex (Fabbro et al., 2000) or left basal ganglia (Abutalebi et al., 2000; Marien et al., 2005). These observations gave rise to the hypothesis that the correct selection of a given language (when the speaker is in a "bilingual mode", see Grosjean, 2001) is under the control of a left prefrontal–basal ganglia neural network (Crinion et al., 2006). However, other clinical reports have also suggested a role for the left supramarginal gyrus in language selection processes (Paradis, 1983 cited in Hernandez et al., 2001). Given these observations, it thus appears that language selection processes rely on a distributed network that might involve both cortical and sub-cortical areas. This hypothesis has recently been supported by the results of functional neuroimaging studies, which indicated that such brain regions might indeed participate in tasks involving language selection processes. For instance, Price et al. (1999) reported that while translation increased activation in the anterior cingulate and sub-cortical–basal ganglia structures, language switching showed higher activations in Broca's area and the bilateral supramarginal gyrus. In picture naming, Hernandez et al. (2001) reported that switching between languages (as compared to non-switching condition) increased activation in the right dorsolateral prefrontal cortex. In another study, Rodriguez-Fornells et al. (2002) used visual presentation of words and pseudo-words to investigate the neural correlates of inhibition processes during lexical access in Catalan–Spanish bilinguals. The comparison of functional responses of bilinguals with those of Spanish monolinguals revealed an enhanced activation of the left anterior prefrontal region (Brodmann areas 45 and 9). Subsequently, Rodriguez-Fornells et al. (2005) investigated mono- and bilingual subjects to assess the degree of phonological interference from the non-target language (as an index of its partial activation, see Grosjean, 2001) when subjects have to tacitly name a picture in a target language. In this strongly mixed language context, the authors observed that phonological interference in bilinguals (as compared to monolingual subjects) was evident in behavioural, electrophysiological and fMRI measures. Particularly, their results suggested that, to control the interference, bilinguals activated non-language-specific brain areas such as the left middle prefrontal cortex (BA 9/46) and the supplementary motor areas. More recently, Crinion et al. (2006) have tested three groups of bilingual subjects during a semantic decision task and showed that responses in left caudate nucleus were sensitive to changes in the language, suggesting that this area might play a major role in monitoring and controlling the language in use. However, since these prefrontal and parietal areas participate also in tasks involving increased cognitive control and executive/attentional demands (D'Esposito et al., 1995; Swainson et al., 2003; Brass et al., 2005; Nebel et al., 2005), the question thus remains whether the language selection process is language-specific or is part of a general executive mechanism (Shallice, 1994) that might participate in switching between various behavioural patterns or even between different linguistic registers.

In this study, we addressed this issue in bilingual subjects by analysing event-related potentials (ERPs) induced by image naming while manipulating two different selection contexts. In the first monolingual context, referred to as "task selection context", the subjects were presented with images and, on the basis of a cue word appearing immediately after each image, they either had to name the image in L1, or to generate a related verb in L1. In the second bilingual context, referred to as "language selection context", subjects were presented with other images and, on the basis of cue words, were required to name the stimulus either in L1 or in L2. Assuming that, in this latter context, the same selection process will be engaged both for naming in L1 and L2, and thus will not differentiate these two conditions, we compared ERP responses to the same L1 naming as a function of context: one context implying an intra-language selection mechanism, the other involving a between-languages selection process. If the neural system responsible for switching between languages is the same as that which underlies the switching from one linguistic register to another, then the electric responses evoked by L1 naming in both contexts will not differ. On the other hand, if these two types of selection processes differ in terms of their neural basis, then the scalp recorded brain responses will diverge relatively rapidly after the presentation of the cue.

2. Materials and methods

2.1. Subjects

Thirteen healthy bilingual young students (11 women and 2 men, mean age = 25 ± 4 years) were recruited from the School of

Translation of the University of Geneva to take part in the experiment. All were right-handed according to the Edinburgh Inventory (Oldfield, 1971) and had a mean laterality quotient of 76 ± 14. All participants had German as a first language (L1) and French as a second language (L2), and all were proficient in L2 based on a formal assessment (see below). They had normal or corrected-to-normal vision and none presented any history of neurological or psychiatric diseases. They all gave formal written consent and were paid for their participation in this study.

2.2. Assessment of language proficiency

All subjects followed their schooling in German since early childhood and started to learn French as their L2 on average at the age of 12 ± 1 years. Prior to their admission to the University, they had all passed the examination allowing them to be admitted to the School of Translation with French as their first active language. At the time of the experiment, all but two had completed their second year of studies successfully and were already engaged in their third year. Before participating in the study, they completed a questionnaire regarding their exposure to languages in areas including media (TV and radio), family, university (classmates and teaching), friends, girlfriends/boyfriends, reading (newspapers and books) and other various activities (hobbies, sports, music, *etc.*) (Wartenburger et al., 2003). This questionnaire indicated that, on a daily basis, they were exposed to L1 on average for 4.5 ± 1.5 h and to L2 for 6 ± 4 h ($p = .3$).

The assessment of proficiency in L2 also included a translation test evaluating the quality and times of translation of L2 to L1 as indices of proficiency. The texts to be translated from French into German were ~150 words long without time constraint. Timing measures were collected using the computer software TRANSLOG2000 (http://www.translog.dk) that tracks all keyboard activity (Jakobsen, 1999) and two independent professional raters assessed the quality of the translation. Finally, we also considered as an index of proficiency in L2 the subjects' performance in the naming task used here (see below).

2.3. Stimuli and experimental procedure

The subjects were tested in a monolingual (L1) *task selection context* (TSc) and in a bilingual (German: L1 *vs* French: L2) *language selection context* (LSc). In order to minimise the possible interference of the bilingual on the monolingual mode, all subjects were first tested in the monolingual TSc and then in the bilingual LSc. In both contexts, the stimuli were black and white images (8.5 × 8.5 cm) representing manufactured objects (tools, furniture, clothes, kitchen objects, electric apparatus, vehicles *etc.*), which were all selected from the Snodgrass and Vanderwart set (1980). Each context consisted of two experimental blocks and used a different set of 70 images. In the TSc, the first experimental block used half of the 70 images ($n = 35$) to generate L1 verbs and the other half ($n = 35$) for L1 naming. In the second block the same images were used in a reverse manner: The 35 images that were used for generating L1 verbs in the first block were now used for L1 naming and the 35 images used for L1 naming in the first block were now used for generating L1 verbs. Taken together, this yielded a total of 140 stimuli of which 70 to generate L1 verbs and 70 for L1 naming. In the LSc, a matched set of 70 other images was used in a similar two-block design. In the first block, the first half of the 70 images ($n = 35$) were used for L1 naming and the other half ($n = 35$) for L2 naming. In the second block, the first half was now used for L2 naming and the other half for L1 naming. Here also, the whole set consisted of 140 stimuli of which 70 for L1 naming and 70 for L2 naming. In each context, the order of the two blocks was balanced over subjects and the two conditions within each block were randomised differently for each subject. For both the TSc and the LSc, a training session of 20 trials was undertaken before the experimental blocks in order to ensure a perfect comprehension of the task demands and to initiate the context. Finally, a rest break of 7 to 10 min was given between contexts to each subject to minimise the effects of fatigue.

In each stimulation trial (of ~4 s duration), an image was presented centrally for 150 ms after a fixation cross that appeared for 1000 ms. Immediately after the presentation of the image, and in order to exclude possible sub-vocal automatic repetition of the image name, a "cue" word was presented for 300 ms to induce the subject's response to the present trial. In the monolingual TSc the German cue word "*VERB*" instructed subjects to generate a corresponding verb in L1 and the German cue word "*NAME*" instructed them to give the name in L1. In the bilingual LSc the German cue word "*DEUTSCH*" was used to induce L1 naming and the French cue word "*FRANÇAIS*" was used to induce L2 naming. A blank screen of 2550 ms followed the cue and allowed for the subjects' verbal responses (see Fig. 1). The subsequent appearance of a central cross informed the participants of the imminence of the following trial and allowed for gaze fixation and the return of the EEG to baseline.

Subjects, seated 120 cm in front of a computer monitor, were recorded in a sound-isolated and electrically shielded room. They were instructed in each context to fix their gaze on the centre of the screen and to attend the cue appearing after each image in order to fulfil each trial demands. In both contexts and for all conditions, the subjects were asked to give an overt oral response as quietly as possible without moving their heads. The experimenter qualitatively and continuously controlled their responses during the whole recording session. However, in order to minimise the experimental constraints during the EEG acquisition session, behavioural responses were recorded and collected in a separate session. In this subsequent behavioural session, both voice onset (as RT) relative to the cue presentation and the subject's actual responses were recorded in order to assess their individual performance. Response accuracy and response times were analysed in each condition and context and were compared statistically.

2.4. EEG recordings and ERP analysis

The EEG was continuously recorded (at 500 Hz, band-pass filtered between 0.1 and 200 Hz) from 111 electrodes (128-

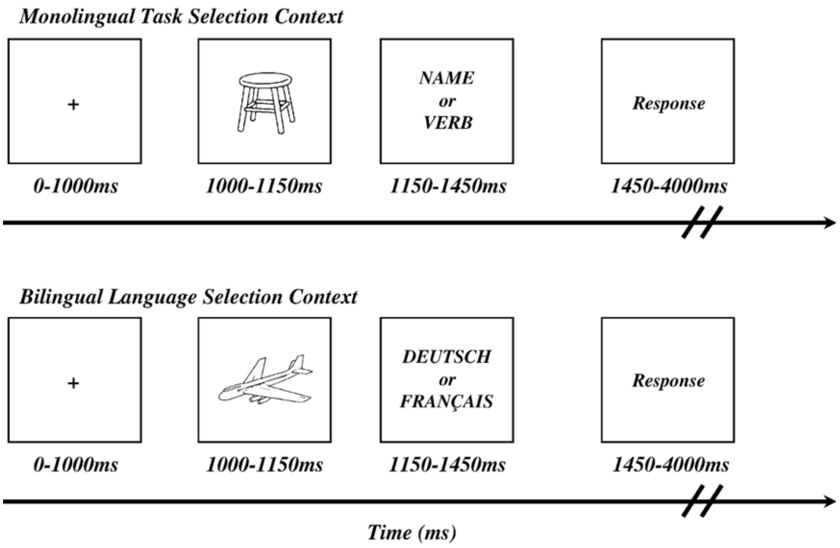

Fig. 1. Schematic representation of the paradigm and sequence of events. In the first monolingual task selection context (TSc), subjects had as a function of the cue word either to name the image or to generate a verb related to it in L1. In the second bilingual language selection context (LSc), they had to name the image either in L1 or in L2 (see Materials and methods).

channels system from Electrical Geodesic, Inc., Oregon, U.S.A) using Cz as the reference electrode. The data were analysed off-line using the Cartool software© for EEG and ERP analysis (v.3.31; http://brainmapping.unige.ch/Cartool.php). ERP epochs were filtered between 1 and 30 Hz and averaged separately for L1 naming condition in each context from −100 ms before the presentation of the stimulus-image to 800 ms post-stimulus (*i.e.* to 650 ms after presentation of the cue word). After eliminating sweeps with amplitude exceeding ±100 μV in any of the channels and excluding, by the visual inspection of the data, all trials containing eye-movement artefacts, the average number (±S.D) of artefact-free trials for L1 naming in TSc and LSc was of 55±9 and 55±13 respectively ($t=-0.15$; $p=.88$, $df=12$). Before computing the grand-mean ERP of each L1 naming condition, the individual ERPs were first recalculated against the average reference. Although the choice of the reference electrode might affect waveform analysis, this choice is completely irrelevant for the strength-independent topographical analysis and for the source localisation estimation that we conducted here (see Michel et al., 2004 and below).

2.5. ERP waveshape analysis

This analysis sought to determine time periods and recording sites where the ERP responses differed between L1 naming in the TSc and in the LSc with respect to the onset of the cue word. For this purpose, point-wise *t*-tests compared the individual ERPs of both conditions at all recording sites and over all time frames (from the cue to 650 ms post-cue). To characterise time periods and sites where reliable response differences occurred, only the significant *t*-values (at $p<.05$) over ten consecutive time frames (20 ms) were retained in this analysis (Jackson et al., 2004).

2.6. Temporal segmentation of ERP map series

In this analysis, we sought to characterise response differences between L1 naming in the TSc and in LSc in terms of the evoked topographic maps. For this purpose, the two average-reference grand-mean ERP map series were analysed using a temporal segmentation procedure based on a *k*-means clustering (Pascual-Marqui et al., 1995). In this type of topographical analysis, but also for source localisation, the choice of the reference electrode is known to be completely irrelevant. For source localisation, this is due to the fact that the inverse solution algorithms which are reference-independent recalculate automatically the signal against the average reference. For the maps in general, this is due to the fact that the configuration of the topography (*i.e.* the distribution of equipotential lines or the map landscape) remains unaffected when changing the reference (see examples in Michel et al., 2004). Here, the use of the average reference is motivated by the fact that the temporal segmentation of ERP map series is a strength-independent analysis. Thus, in order to eliminate simple strength differences between conditions and to search only for differing topographies, the segmentation procedure normalizes the ERP map series by diving each time point by its own global field power (GFP) value. The GFP corresponds to the spatial standard deviation of the average-reference maps and thus measures the strength of the global electric field at each time point (Lehmann, 1987).

In brief, the segmentation procedure allows in a first step to define the optimal number of topographic maps that explain the most dominant field configurations found in the grand-mean ERP map series, and in a second step to assess the presence of the maps found in the grand-mean segments in each individual ERP of each condition (Pegna et al., 1997, 2002; Khateb et al., 2000, 2001, 2003; Morand et al., 2000; Ducommun et al., 2002; Blanke et al., 2005; Thierry et al., 2006, 2007). Thus, using the spatial clustering procedure, we identify periods of quasi-stable map topographies (*i.e.* similar field configuration) and compute for each period the mean map that represents the topography of this period. Once these mean maps (referred to also as “segment maps”) are defined, their specificity for a given condition is verified by fitting them to the individual ERP map series in each

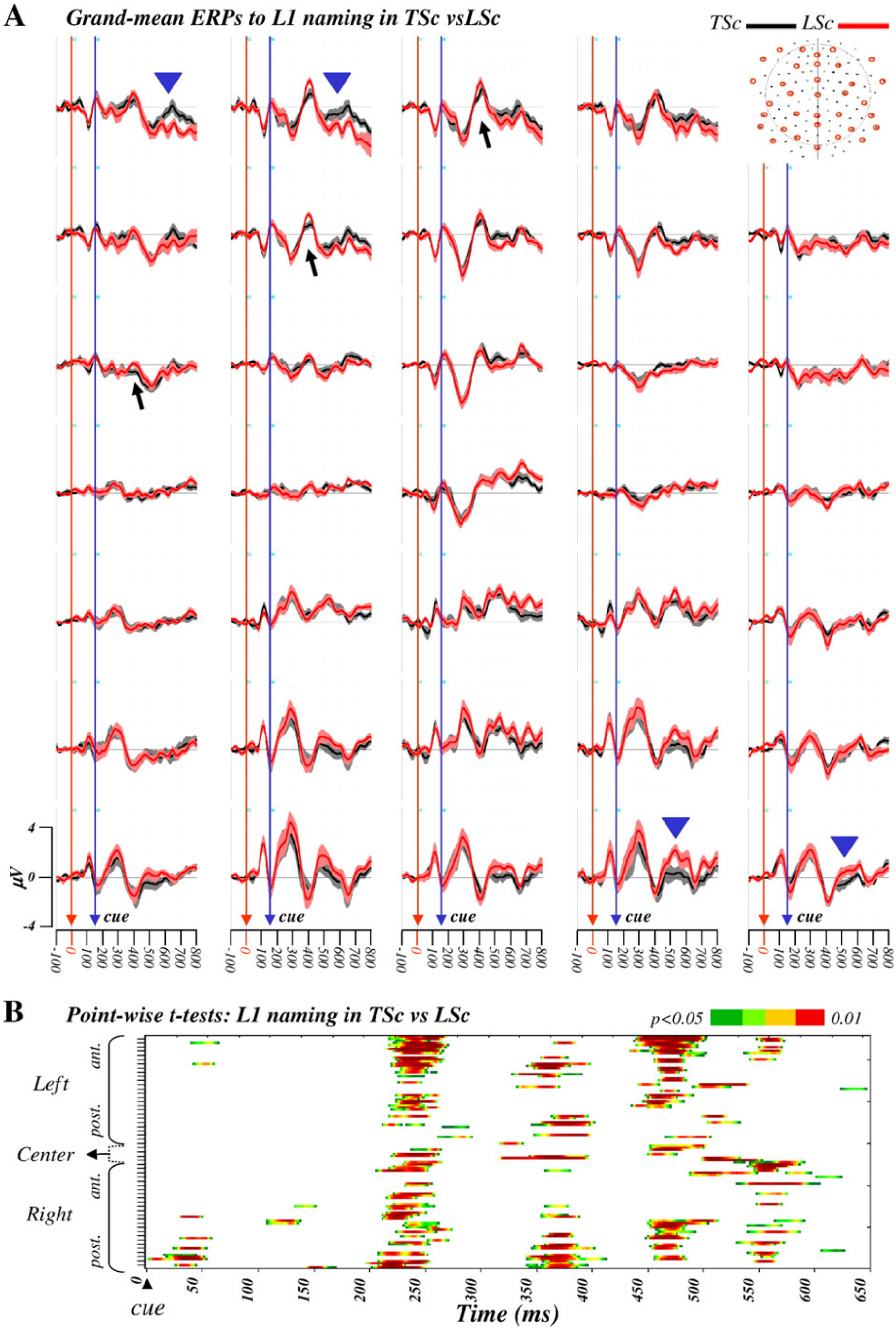

Fig. 2. ERP waveform analysis. A: Superimposed grand-mean ERP (±SEM) traces from TSc (black lines) and LSc (red lines) showing a subset of 34 electrodes over the whole scalp that highlights the major amplitude differences between contexts over time. The electrode schema in the upper right row indicates the position of the selected sites for this illustration with nose in the front and left at left. The traces are displayed with a 100 ms baseline before the image-stimulus onset (at 0 ms, red vertical lines) to 800 ms post-stimulus. The posterior sites (the lowest row) illustrate the exogenous visual responses to the image: the P100, the N150 and the P2 components, respectively at 100, 150 and ~250 ms. Note that the onset of the cue word (blue vertical lines), at 150 ms after the image onset, coincides with the peak of the N150, and that the expected P100 exogenous response to the cue coincides with the ascending phase of the image-related P2. Hence, the cue-related P100 mixes with the image-related P2 and can’t be clearly dissociated. Note that, based on our working hypothesis, the following analyses will focus on the post-cue period (*i.e.* cue onset to 650 ms). B: Point-wise *t*-tests comparing individual ERPs to L1 naming in TSc and LSc from cue onset to 650 ms after. The graph illustrates the significant *p* values over time and recording sites (the 111 electrodes) and shows that the first major differences involving a large number of electrodes occurred at ~220 ms post-cue. As displayed in panel A, these differences were the most prominent over left frontal sites (see arrowheads on left anterior sites, panel A). Other later differences appeared also at around 350 and 450 ms. These differences were also widespread and affected both left anterior and right posterior sites (see blue triangles in panel A). Colour scale indicates *p* values of 0.05 to 0.01.

context. Concretely, we calculate a spatial correlation coefficient (Brandeis et al., 1992) between each segment map and each map in the subject's individual map series (Pegna et al., 1997; Khateb et al., 1999), and then each time point in the individual map series is labelled with the segment map it is most highly correlated with. Afterwards, different timing and spatial measures can be extracted for each segment map, particularly the segment duration which refers to how many times each template segment map appeared in each individual ERP map series. Here, we compared statistically the segment duration parameter for determining condition-specific segment maps (*i.e.* those appearing preferentially in one but not in the other condition) and those that are present in two conditions but might differ in terms of duration.

2.7. Source localisation analysis

This analysis used the LAURA inverse solution (Grave de Peralta Menedez et al., 2001) to estimate brain regions that gave rise to electric field differences between the two contexts. LAURA is a distributed linear inverse solution calculated on a realistic head model that includes 4024 solutions points (*i.e.* voxels) equally distributed within the cortical and sub-cortical grey matter of the average brain (Montreal Neurological Institute, Montreal, Canada). Similar to other distributed inverse solutions, LAURA is capable of dealing with *a priori* unknown number and location of simultaneously active sources in the brain (Ducommun et al., 2002; Khateb et al., 2003; Ortigue et al., 2004; Blanke et al., 2005; Thierry et al., 2006). Here, we first applied LAURA to the individual ERP time segments of interest. We then contrasted the individual estimated inverse solutions of LSc *vs* TSc using *t*-tests in order to determine brain regions that were more significantly activated (at $p<.01$) during the language selection context.

3. Results

3.1. Behavioural results

The results of the translation test using TRANSLOG indicated that the quality scores were high and homogenous among the group (mean score = 56 ± 7 out of 80), except in one subject who showed a relatively poorer score (34/80). The subjects' performance in the monolingual TSc showed a mean correct response rate of 95 ± 3% in verb generation and of 96 ± 2% in L1 naming ($p=.6$). In the bilingual LSc, the subjects showed a mean correct response rate of 95 ± 3% in L1 naming and of 85 ± 10% in L2 naming ($t=4.4$; $p<.001$; $df=12$). More particularly for our purpose, no performance difference was observed in L1 naming between TSc and LSc ($p=.83$). Concerning the response times (RTs), the TSc and the LSc yielded globally similar RTs, indicating that difficulty over contexts was highly comparable (mean RT = 1160 ± 140 and 1176 ± 138 ms, respectively in TSc and LSc; $p=.45$). Within the TSc, verb generation took longer time than L1 naming (mean = 1202 ± 144 and 1117 ± 145 ms respectively; t ± 4.1; $p<.002$; $df=12$). In the LSc, response times for L1 naming did not differ significantly from those for L2 naming (1156 ± 130 and 1196 ± 170 ms respectively; $p=.29$). In particular for our purpose, RTs in L1 naming were slightly longer in LSc than in TSc, but this difference failed to reach significance (1156 ± 130 and 1117 ± 145 ms respectively, $t=1.98$; $p<.073$; $df=12$).

3.2. Analysis of ERP waveforms

The analysis aimed at identifying the earliest responses differentiating L1 naming in the two contexts after cue onset. Fig. 2A shows on a subset of recording sites the superposition of the averaged waveforms (±SEM) induced by L1 naming condition in TSc and LSc from −100 ms before the image (stimulus) onset to 800 ms post-stimulus (*i.e.* 650 ms post-cue). This illustration shows that some response differences appeared relatively early after the cue onset (see arrowhead on left anterior sites), but that other differences were also found later (see triangles on left anterior and right posterior sites). In particular and as expected, the most posterior sites (the lowest row) that depict the primary visual responses in relation with image presentation (successively the P100, N150 and P2 components, at 100, 150 and ~250 ms respectively) suggest no response difference during these early components. Of note also is the fact that the cue-expected P100 response coincides with the ongoing image-related P2, and thus can't be dissociated here.

In order to assess statistically the response differences between L1 naming in TSc and LSc, we compared the individual ERP of the two contexts from the cue onset to 650 ms post-cue (*i.e.* 800 ms post-image) using point-wise *t*-tests. As shown in Fig. 2B, which depicts the significant *p* values over time and recording sites, the first major differences appeared at around 220 ms post-cue and lasted up to 300 ms. These differences concerned various scalp locations but were most prominent at left anterior recording sites (see examples on Fig. 2A, arrowheads). Although of lesser significance to our working hypothesis, other later differences were also confirmed between ~350–400 ms and slightly after the 450 ms time range. As expected from the visual inspection of the grand-mean ERPs, these later differences involved both left anterior and right posterior scalp regions (see examples in Fig. 2A, triangles).

3.3. Temporal segmentation of ERP map series

This analysis sought to characterise response differences between the two contexts in terms of the electric field topographies. The strength-independent segmentation of ERP map series of L1 naming in TSc and LSc showed that a total of 18 topographic template maps (see Fig. 3A) explained the whole dataset. Figure 3B illustrates the time segments of stable topographical configuration where these maps occurred in the grand-mean ERPs. It shows that the same sequence of segments was found in the two contexts up to around 200 ms and then some maps appeared only in the TSc (*e.g.* maps #5 and #6) or in the LSc grand-mean (*e.g.* map #7). This suggested that this same period, where amplitude differences were also found through waveform statistical comparison, differentiated contexts also in terms of the

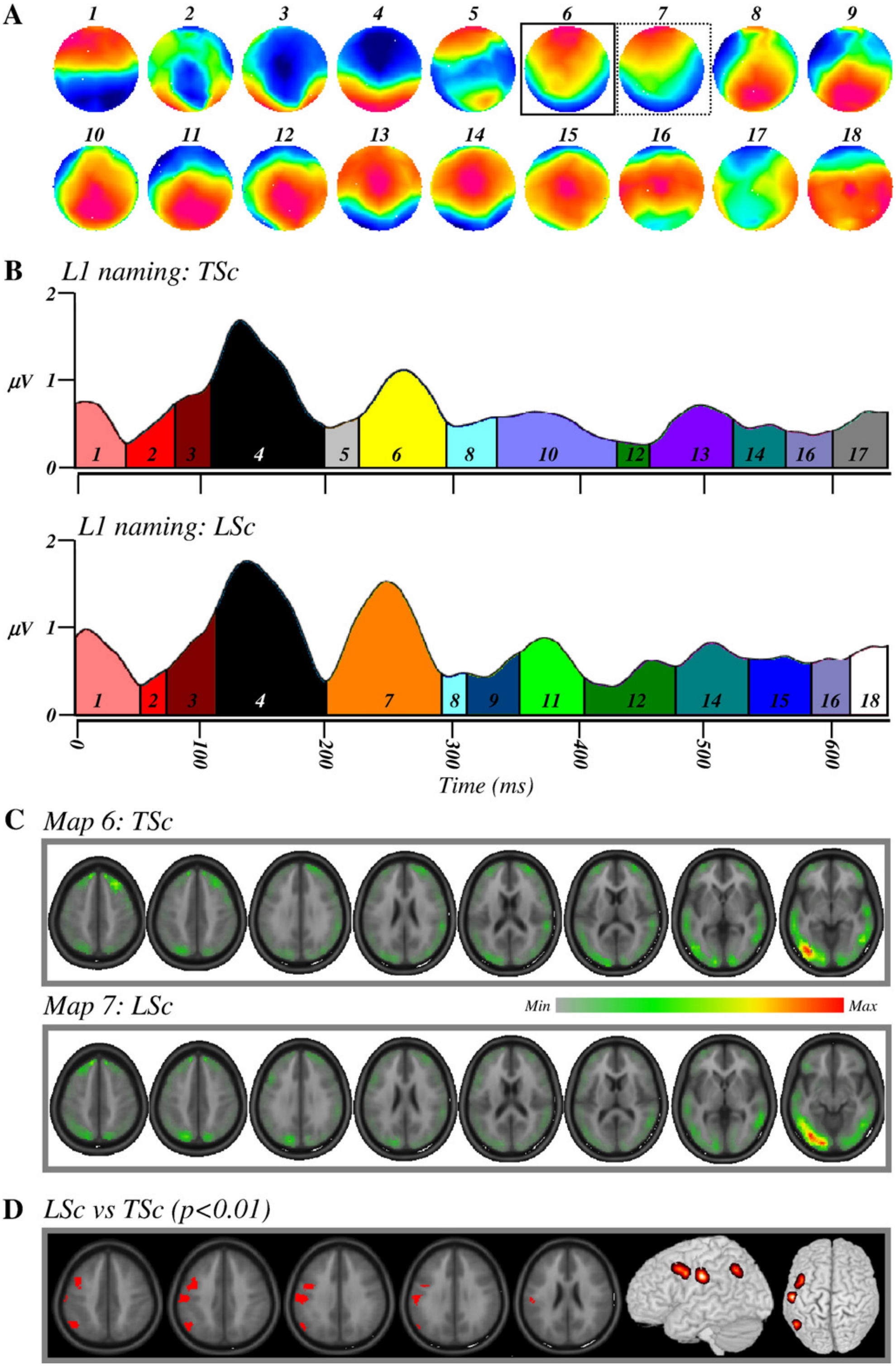

Fig. 3. Temporal segmentation of the grand-mean ERP map series and source localisation analysis. A: The 18 topographic maps that explained the dominant field configurations found in the grand-mean ERP map series of L1 naming in TSc and LSc as revealed by the temporal segmentation procedure. The maps are shown from top with left ear left. Blue values indicate negative potentials, red values positive potentials. B: Global field power traces (see Materials and methods) of the grand-mean ERPs of L1 naming in TSc and LSc showing the time segments of stable map configuration (referred to as functional microstates) where these maps occurred in each context. As in the waveform analysis, the first major differences appeared between 200 and 300 ms as attested by the dominant presence of map 6 in TSc only and of map 7 in LSc only. C: Axial MRI slices illustrating the mean inverse solutions over subjects for the period 220–270 ms (periods of map 6 and 7) in TSc and LSc and showing similar source distribution with particularly the dominant activation of the bilateral inferior and middle occipital gyri (see text for the other regions). Note that the two solutions have the same intensity scale and that left is one left. D: Axial MRI slices and 3D brain images showing the results of the statistical analysis that contrasted the individual LSc and TSc inverse solutions during the 220–270 ms time period. The brain regions differentiating LSc and TSc (at $p<.01$) indicated a stronger involvement of left fronto-parietal regions during LSc.

global electric field configuration and thus presumably of the underlying cerebral generators.

In order to verify this hypothesis statistically, we assessed the presence of the segments' maps (referred to as "segments' duration", see Materials and methods) in the individual L1 naming ERPs of both contexts. For that, we looked for the maps 1 to 7 in the time window between 0 and 320 and for maps 8–18 in the time window between 310 and 650 ms. In the first time window, the 2×7 ANOVA performed on segments' duration using contexts (2) and maps (7) as within subjects' factors showed a highly significant main effect for maps ($F(6, 72)=14.4$, $p<.000001$) due to the fact that the successive segments had varying durations. More interestingly, the highly significant interaction, observed between the two analysis factors ($F(6, 72)=3.8$, $p<.0025$), indicated that some maps' durations differed between conditions. *Post-hoc* Fisher's LSD tests indeed showed that map segments #6 and #7 significantly differentiated contexts. Thus, map #6 was confirmed to occur more frequently in TSc (59±37 ms) than in LSc (34±20 ms, $p<.002$), while map #7 was more present in LSc (68±31) than in TSc (43±37 ms, $p<.0015$).

Although of lesser interest to our purpose, the 2×11 ANOVA performed on the duration of the latter segments' maps (the 11 remaining maps) showed again a highly significant main effect for map ($F(10, 120)=5.4$, $p<.000001$), and a significant interaction between the analysis factors ($F(10, 120)=3.4$, $p<.0007$). *Post-hoc* Fischer's LSD tests indeed showed that: map 13 was found more frequently in TSc (103±82 ms) than in LSc (58±47 ms, $p<.0003$); map 15 was more present in LSc (32±20 ms) than in TSc (4±7 ms, $p<.025$); and that map 17 was more present in TSc (53±60 ms) than in LSc (22±31 ms, $p<.01$). Of note is the fact that the duration in the individual ERPs of segments' maps 10, 12 and 18 followed the same tendency as in the grand-mean segmentation (see Fig. 3B), but that the durations' differences did not reach the statistical significance.

3.4. Source localisation analysis

This analysis aimed at estimating brain regions accounting for the first field configuration differences between LSc and TSc and represented by segments' maps #7 and #6. For that, a mean map was first calculated from each individual L1 naming ERP of each context in the time period between 220 and 270 ms. These maps were then individually subjected to the inverse solution algorithm (LAURA) and a *t*-test contrasting LSc *vs* TSc was afterwards computed on the current density of all the LAURA solution points (*i.e.* voxels). Fig. 3C, which illustrates the mean inverse solution across subjects for this time period, shows that the dominant activation in TSc and LSc was globally found in similar brain regions. These included principally the inferior and middle occipital gyri bilaterally (although more dominant in the left), the bilateral temporal gyrus but more dominantly in the left, the superior, middle and inferior frontal gyri, and the superior and inferior parietal lobules. Fig. 3D depicts the brain regions where the estimated individual activation significantly differentiated LSc from TSc. It shows that this time period in LSc recruited differently left hemispheric frontal and parietal areas. Antero-posteriorly, the localisation of the activated areas according to the Talairach and Tournoux's coordinates (Talairach and Tournoux, 1988) revealed the involvement at the frontal level of the middle frontal–precentral gyri (BAs 9/6; *x*,*y*,*z* at the centre of gravity of the cluster=−58, 1, 43) and at the parietal level of the supramarginal gyrus (BA 40/2; −62, −21, 35) and the angular gyrus (BA 39; −51, −62, 41).

4. Discussion

The aim of the present investigation was to determine whether the cognitive mechanism that allows bilingual speakers to select one language rather than another is different from that which allows the selection between various behavioural patterns including the different linguistic registers. To address this question, we analysed electric responses (ERP waveforms and map series) evoked by the same L1 naming condition as a function of two selection contexts: a monolingual (or intra-language) task selection context (TSc) and a bilingual (or between languages) language selection context (LSc). The rationale was that if the between-language selection process differs from the intra-language task selection process, then electric brain responses should differentiate these two (otherwise exactly similar) L1 naming conditions. This design diverges significantly from other paradigms that manipulate language switching with a predictable task-sequence (Rogers and Monsell, 1995), which thus allows for the assessment of the switching costs in terms of response time and errors (see Jackson et al., 2001; Swainson et al., 2003). Here, the presentation of the different conditions in each selection context was randomised in another way for each subject, with a trial-by-trial cuing (Meiran, 1996) and without any predictable order. The random naming in L1 and L2 in LSc was a necessary manipulation in order to create the context of between-languages selection, which was contrasted with that of intra-language task selection.

Behaviourally, the analysis of subjects' correct responses in L1 naming in LSc and TSc showed a highly similar performance across contexts, indicating that task difficulty was highly comparable. In terms of response speed, although reaction times (RTs) for L1 naming did not differ significantly between contexts, our results show a trend towards longer RTs (of ~40 ms) in LSc than in TSc. This additional time in LSc, presumably due to switching costs, fits within the range of values estimated by previous studies (*e.g.* 25 ms in Jackson et al., 2004 and 102 ms in Jackson et al., 2001). In comparison to Hernandez et al.'s study (2001) where image naming conditions were used, our results show that the RTs measured here for L1 naming in both contexts were considerably longer than those previously reported. However, it should be noted that in the study of Hernandez et al. (2001) the cue was presented before the images while in our study it was presented after the images. This increase in RTs corroborates thus previous finding showing that switching, which is a time-consuming process, delays response selection if it occurs after target presentation (Swainson et al., 2006). Presenting a cue before the lexical item is thought to abolish costs related to in-between-language selection processes since selection is limited only to items within a single language lexicon, a process similar to word production in monolinguals (see Grosjean, 1998). This might explain why in Hernadez et al.'s functional study (2001) no significant activation was found in left hemisphere language control areas when comparing switching between languages to no-switching condition. In our study, the bilingual subjects have first to enter the hypothesised common conceptual representation for the two languages and then language selection took place to retrieve the correct lexical items (supposedly with the concomitant inhibition of the non-target language).

At the electrophysiological level, we predicted that if the selection processes involved in the two contexts were different in terms of their neural basis, then the electrical responses evoked by the two L1 naming conditions should diverge relatively early after the analysis of the cues. The analysis of ERP waveforms in terms of response amplitude confirmed our prediction by showing that the earliest major differences appeared at around 220 ms after the presentation of the cue and peaked at around 250 ms. The strength-independent topographical analysis of ERP map series confirmed that this same time period differentiated contexts in terms of the electric field topographies. Actually, it revealed that, while L1 naming in LSc and in TSc showed the same succession of microstates up to ~200 ms, the period between ~200 and 300 ms was dominantly characterised by the presence of one microstate (segment #6) in TSc and by another one (segment #7) in LSc, each having its distinct electric field configuration. Assuming that the two L1 naming conditions differed only in terms of the selection process involved, it appears reasonable to assume that these early electrophysiological differences represent the correlates of the differing processes involved, and thus that the neural responses underlying the between-language selection could differ from those involved in the switching from one linguistic register to another.

In a previous ERP study, Jackson et al. (2001) investigated the time course of language switching in bilingual speakers using a predictable productive switching task. They reported that switch trials, compared with non-switch trials, increased the frontal N2 negativity (at around 320 ms) and this is only for L2 trials. Later on, they found a modulation of a late positive component (LPC, between 350 and 700 ms) for switch trials in both languages. The authors proposed that the modulation of the frontal N2 might reflect the suppression of the habitual response (L1) during L2 switch trials (Meuter and Allport, 1999) and suggested that this interpretation was compatible with Green's Inhibitory Control Model of language switching (Green, 1998). Concerning the modulation of the LPC by switch trials in both languages, the authors interpreted it as reflecting the reconfiguration of the language-specific phonology-to-articulatory sets on the basis of the cue. In a subsequent study, the authors investigated a receptive language switching (Jackson et al., 2004) using number words presented in L1 and L2. Subjects were required, using motor responses, to judge whether the words were odd or even. In this later study, they failed to observe the frontal and parietal switch-related activity, previously reported in the productive switching task (Jackson et al., 2001). However, they reported an early switch-related activity on central electrodes that was not language-specific. In a within-sentence switching paradigm, Proverbio et al. (2004) used visual presentation of unmixed (one language) and mixed (mixing languages at the final word) sentences and observed that the first effect of lexical and code switching was found between 140 and 200 ms at left anterior sites. Due to the differences in the paradigms used, no direct comparison could be made between our results and those of these previous studies. However, it is worth noting that in these studies, as in our present findings, the first language switch-related modulation of the ERP concerned more particularly the left anterior sites, showing thus a certain consistency across studies and this is independent of the paradigms used. Nevertheless, we hypothesise that the relatively early LSc-induced response observed here is not related to L1 suppression (as suggested by Jackson et al., 2001) since the comparisons performed here concerned in both contexts the L1 naming. In the language selection dual-schema context (*i.e.* naming in L1 or name in L2, von Studnitz and Green, 1997) that we designed here, these highly proficient bilingual subjects performed the task according to a strongly mixed bilingual mode in which they had to switch continuously between their L1 and L2 and this is in a completely random fashion. Although, we intentionally did not compare directly the ERPs to L1 and L2 naming to avoid interpreting hazardously the ERP differences that can be due merely to differing proficiency levels between the two languages, we speculate that in such a context, the language selection process, which is supposed to deactivate the lexicon of the non-target language (Green, 1998), is the same whether the subjects have to name images in L1 or in L2.

Although of a lesser importance to our hypothesis, the later ERP differences, which we observed here between ~350 and 500 ms post-cue, appeared at posterior (central and right) sites as an increased positivity for LSc as compared to TSc and as an increased negativity for LSc *vs* TSc at anterior left sites. The analysis of the different segment maps occurring during this second time period confirmed that some of the maps were found more specifically in TSc (*e.g.* segment map 13) while others were found in LSc (*e.g.* map 15). Of note here is the fact that the modulation of our late responses resembles that found previously in Jackson et al.'s (2001) study using the productive switching task (see above). Actually, in their average-reference ERP results, the authors reported that switch-related modulation of the LPC (350–700 ms) affected principally the parietal sites. However, it is important to note that the augmented LPC for the switch conditions in their results was accompanied at the frontal sites with an increased negativity exactly as we found here. Given the fact that both studies (Jackson et al. and ours) used language production tasks, it is thus reasonable to assume that the late response difference between LSc and TSc might be due to the reconfiguration of the language-specific phonology-to-articulatory sets: In our highly mixed LSc a language switch was roughly required on a trial-by-trial basis, a process that is not required for L1 naming in the TSc. Finally, one should also not exclude the possibility that the small RT difference between L1 naming in TSc and LSC might have slightly contributed to the late ERP differences.

Although to be interpreted with caution due to the relatively limited spatial resolution of these techniques, the mean inverse solution revealed in both contexts the dominant involvement of the occipital areas, but also of other frontal, temporal and parietal regions. The dominant activation of the occipital areas is consistent with the fact that this period coincide with that of an increased posterior negativity (the ERP N2 component) where bilateral posterior activation had previously been reported in relation with pictorial processing (Doniger et al., 2000; Khateb et al., 2002). More particularly, the statistical comparison of the individually estimated sources during this time period showed that brain regions differentiating LSc from TSc involved a subset of areas known for their participation in various language and cognitive tasks (see Duncan and Owen, 2000; Miller, 2000; Brass et al., 2005; Vigneau et al., 2006). A point of interest here is the fact that these areas were restricted to the left hemisphere, corroborating thus previous clinical observations indicating that left lesions may be responsible for producing language switching difficulties (Marien et al., 2005). As already pointed out in other switching studies (Price et al., 1999), the fronto-parietal areas described here were found outside of the classical Broca and Wernicke language areas. The frontal activation covered partially the posterior prefrontal cortex (BA 9). The prefrontal cortex, which constitutes a large cortical region, had repeatedly been proposed by clinical and functional studies to participate in cognitive control and switching processes (Owen et al., 1993; Dove et al., 2000; Duncan and Owen, 2000), and particularly in language selection processes in bilinguals (Fabbro et al., 2000; Hernandez et al., 2001; Rodriguez-Fornells et al., 2002, 2005). For instance Rodriguez-Fornells et al. (2005) have recently suggested that the recruitment of the left prefrontal cortex (BA 9/46), a typical 'executive function' brain area, might be crucial in inhibiting the production of the non-target language when subjects had to name a picture in the target language. The prefrontal cortex, which has also been implicated in working memory and divided attention (Miller, 2000; Raye et al., 2002; Nebel et al., 2005), has been involved in a variety of language paradigms including word generation, semantic categorisation, semantic fluency and rhyme detection tasks (see Seghier et al., 2004; Vigneau et al., 2006), confirming thus the participation of the prefrontal regions to various task sets (Dosenbach et al., 2006). Similarly, the motor areas and more specifically the precentral gyrus were also found in most language studies (Vigneau et al., 2006) and associated not only with articulatory planning and execution but also with speech perception (Pulvermuller et al., 2006).

Together with the frontal region, we observed also significant difference in the anterior part of the left supramarginal gyrus (BA 40) and in the left angular gyrus (BA39), both areas previously found in various language studies. In particular, the supramarginal gyrus has been often involved in phonological processes (*e.g.* mapping orthography to phonology, phonological recoding, rhyme detection *etc.*, see Paulesu et al., 1993; Demonet et al., 1994; Seghier et al., 2004), while the angular gyrus has been involved in semantic processing (Binder et al., 1997; Price, 2000; Binder et al., 2005). The activation here is also in accordance with previous clinical observations suggesting a role for the supramarginal gyrus in language switching (Paradis, 1983; Hernandez et al., 2001). In line with this finding, Price et al. (1999) have previously shown that language switching is associated with an increased activation in the bilateral supramarginal gyri. Related to these observations, a recent fMRI study (Venkatraman et al., 2006) showed that language switching effects during exact arithmetic additions were found in the left inferior frontal gyrus and the left inferior parietal lobule extending to the angular gyrus. Also, a specific role for the inferior parietal lobule in the bilingual brain has recently been supported by studies using whole-brain mapping techniques. Actually, Mechelli et al. (2004) showed that acquiring the vocabulary of a second language (L2, English in Italian native speakers) induced structural changes in the inferior parietal cortex as attested by grey matter density increases as a function of language proficiency. Interestingly, the same brain region was referred to as the 'language switching talent area' by the classical German aphasiological literature (Poetzl, 1925, 1930; Leischner, 1948).

Contrary to other studies where a specific activation of the left dorsolateral prefrontal cortex has been observed (Hernandez et al., 2001), our analysis did not reveal the particular activation of this area in this context. This region, which has been found in various other contexts requiring increased cognitive control such as task switching and divided/focused attention (D'Esposito et al., 1995; Swainson et al., 2003; Brass et al., 2005; Nebel et al., 2005), might have been involved similarly in our monolingual TSc and bilingual LSc during this specific time period, and thus did not appear in this statistical comparison. Likewise, differing from clinical (Abutalebi et al., 2000; Marien et al., 2005) and recent functional imaging studies (Crinion et al., 2006) where the left caudate nucleus has been involved in language selection, our analysis did not show the activation of this specific area. In Crinion et al.'s study (2006) where semantic decision task was used in bilinguals, it has been indicated that the left caudate responses were highest not only when there was a change in language but also when a change in word meaning occurred. It is worth noting that other clinical reports in monolingual patients indicated that the left caudate damage might be associated with naming and word-finding difficulties, thus suggesting that its lesion might impair the patients' ability to select the appropriate lexical–semantic responses (see Crinion et al., 2006). In view of such observations, it is likely that the caudate nucleus had also been engaged during the lexical switching from one linguistic register to another during TSc and thus did not appear in our analysis. The possibility that the caudate nucleus was not involved at all during this processing step should also not be excluded. Indeed, a recent review by Friederici (2006) suggested that the left caudate nucleus, which participates to a variety of language tasks, thanks to its connections with the frontal, motor and temporo-parietal cortex, might activate when the language processing system cannot rely entirely on automatic mechanisms. The late ERP differences between LSc and TSc (but also the slight increase of RTs in LSc), which might presumably be linked to phonological re-mapping process, strongly indicate that L1 naming in the bilingual context was achieved through more controlled than in L1 naming in the monolingual context. Thus, one could not rule out that the left caudate nucleus (but also other areas involved in cognitive control) was engaged during other steps of information processing.

To conclude, our results point to the participation of fronto-parietal areas in language selection processes. The involvement of these regions in language processing network has recently been supported by a diffusion tensor imaging study that described a connection between the posterior frontal cortex (in particular the middle frontal gyrus) and the inferior parietal cortex (precisely BA 40 and 39, Catani et al., 2005). This observation, together with the fact that the brain areas found here were also shown to participate in the processing of various linguistic processes indicates that language selection might rely not only on regions involved in cognitive control but also on other neural modules that are part of the extended language neural network defined by recent neuroimaging studies. Further studies comparing language and non-language switching paradigms are however required to substantiate the specific role of such areas in the early steps of language selection processes.

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