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Barbara Köpke, Ruairidh K R Howells, Francesca Cortelazzo, Patrice Péran, Xavier de Boissezon, Vincent Lubrano

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# Functional and structural differences in brain networks involved in language processing and control in highly proficient early and late bilinguals

## Authors:

Barbara Köpke

Octogone-Lordat, Université de Toulouse, UT2J, Toulouse, France  
ORCID 0000-0003-1634-3457

Ruairidh K R Howells

Toulouse NeuroImaging Centre, UMR1214, Université de Toulouse, Inserm, UPS,  
Toulouse, France  
ORCID 0000-0002-8838-6088  
Corresponding author, [ruairidh.howells@inserm.fr](mailto:ruairidh.howells@inserm.fr)

Francesca Cortelazzo

Octogone-Lordat, Université de Toulouse, UT2J, Toulouse, France  
Toulouse NeuroImaging Centre, UMR1214, Université de Toulouse, Inserm, UPS,  
Toulouse, France

Patrice Péran

Toulouse NeuroImaging Centre, UMR1214, Université de Toulouse, Inserm, UPS,  
Toulouse, France  
ORCID 0000-0001-7200-0139

Xavier de Boissezon

Toulouse NeuroImaging Centre, UMR1214, Université de Toulouse, Inserm, UPS,  
Toulouse, France Service de médecine physique et réadaptation, Centre Hospitalier  
Universitaire, Toulouse, France

Vincent Lubrano

Toulouse NeuroImaging Centre, UMR1214, Université de Toulouse, Inserm, UPS,  
Toulouse, France

Department of Neurosurgery, Centre Hospitalier Universitaire, Toulouse, France  
Clinique de l'Union, Saint-Jean, France

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## Abstract

Age of acquisition and proficiency have been identified as possible determinants in the neural localization of second language representation and in the nature of control mechanisms. However, the relationship is not yet clear between age of acquisition and proficiency on the one hand, and language switching and executive functions on the other. In the present study, we used anatomical and functional Magnetic Resonance (MR) Imaging to investigate the impact of age of acquisition. Two groups of highly proficient early and late bilinguals, carefully matched in other measures of proficiency, performed an overt picture-naming task in blocked and switched conditions.

We found that switching between languages in highly proficient bilinguals involves an increase of activity in areas reported as components associated with domain-general inhibitory processes. There was no effect of task language, only of whether the task involved language switching. Comparing the two groups indicated that highly proficient bilinguals use the same neural network for language production and

control regardless of age of acquisition. Structural differences were apparent between the two groups in regions associated with language control.

We propose that language switching recruits a neural network that is engaged for domain-general executive control functions and that proficiency rather than age of acquisition exerts influence on language representations.

**Keywords:** fMRI; language processing; bilingualism; executive function; proficiency; age of acquisition.

## Introduction

The neural correlates of languages and language processing in bilingual speakers have been the subject of lively debate. This debate has mainly focused on two questions.

The first question concerns the neural representation of each language, namely whether these are represented in distinct or overlapping networks. Two prominent factors have been identified as possible determinants in bilingual language representation: age of acquisition (AoA) and proficiency. One might expect that age-related effects could alter the neural localization of second language representation, due to a shift of the memory systems used for processing a later-learned language (L2) (Ullman, 2001). Alternatively, a proficiency-based hypothesis suggests that the neural representation of the first language (L1) and L2 will converge once advanced L2 proficiency is reached (Green, 2003). Results from studies based on functional fMRI have yielded inconsistent results (see e.g., Blackburn 2019 for a review of studies) and do not provide a clear picture of the role of the experiential factors involved, mainly AoA and proficiency. Few studies involve both early and late bilinguals and proficiency is most of the time assessed through self-evaluations only. Among the exceptions, Martin et al. (2015) tested early and late bilinguals in an ERP study with a language switch task involving a weaker third language and found that the two groups differed in the way they controlled language. However, the late bilinguals in this group had not achieved native-like proficiency in L2, so the groups differed with respect to both AoA and proficiency. Wattendorf et al. (2014) controlled for proficiency with a language task and tested multilingual, educated participants with various language combinations (involving mainly German, French and Italian) in

a narrative task and found higher activation of a left fronto-striatal network in early bilinguals, while later bilinguals relied more heavily on the left posterior superior temporal gyrus (pSTG). The findings were interpreted as being due to the reliance on different control networks, an issue that has in recent years progressively replaced the question about distinct or overlapping processing networks for each language in bilingualism research.

Then, the second question concerns the ability of bilingual speakers to keep their two languages apart with the help of a mechanism referred to as bilingual language control (Abutalebi & Green, 2007; Hernandez, 2009; Price, Green & von Studnitz, 1999). The literature on bilingual language processing generally agrees on the fact that some sort of attentional control mechanism is involved in bilingual lexical access (e.g., Costa, Hernandez & Sebastián-Gallés, 2008; Finkbeiner, Almeida, Janssen & Caramazza, 2006; Green, 1998; Hermans, Bongaerts, de Bot & Schreuder, 1998; Kroll, Bobb & Wodniecka, 2006). For instance, the influential Inhibitory Control model (Green, 1998), requires active inhibition to suppress the representations of the language not in use.

Clinical studies, reporting cases of bilingual patients, have helped identify regions involved in language control. For instance, patients with a lesion to the left prefrontal cortex and anterior cingulate cortex (ACC) showed pathological language switching, whereas lesions in the parietotemporal region and left caudate may cause pathological mixing (Abutalebi, Miozzo, & Cappa, 2000; Fabbro, Skrap, & Aglioti, 2000). Pathological fixation on one language has been related to lesions to the basal ganglia (Aglioti, Beltramello, Girardi, & Fabbro, 1996).

More recently, neuroimaging studies seem to agree that language switching is subtended by a cortico-subcortical network involved, at least partially, in domain-general cognitive control (Abutalebi & Green, 2007; Hervais-Adelman, Moser-Mercer, & Golestani, 2011) rather than a particular switch area as believed earlier (Poetzl, 1930). The language control network involves fronto-parietal cortical areas and subcortical regions (Massa, Cortelazzo, El Yagoubi, & Köpke, 2016) and includes the superior temporal sulcus (Abutalebi et al., 2008; Rodriguez-Fornells, Rotte, Heinze, Nösselt, & Münte, 2002), superior and inferior parietal lobule (Costa, Hernandez, Costa-Faidella, & Sebastian-Galles, 2009; Khateb et al., 2007; Price, Green, & Von Studnitz, 1999; Rodriguez-Fornells et al., 2002; Wang, Kuhl, Chen, & Dong, 2009), supplementary motor area (SMA; Abutalebi et al., 2008; Wang, Xue,

Chen, Xue, & Dong, 2007), dorsolateral prefrontal cortex (DLPFC; Abutalebi et al., 2008; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Khateb et al., 2007; Wang et al., 2009), inferior frontal gyrus (IFG; Abutalebi et al., 2008; Hernandez et al., 2001; Price et al., 1999; Rodriguez-Fornells et al., 2002), precentral gyrus (Khateb et al., 2007; Wang et al., 2009), and ACC (Abutalebi et al., 2008, 2012; Crinion et al., 2006; Wang et al., 2007).

Direct evidence for brain regions involved in language control comes from stimulation mapping studies. Kho et al. (2007) induced unintentional language switching in two patients: in the first, language switching occurred during a Wada test in the left hemisphere, the second switched from French to Chinese when stimulated in the posterior left IFG. Lubrano et al. (2012) reported involuntary language switching during a picture naming task while the DLPFC was stimulated (see also Sierpowska et al., 2013, for similar results).

Similarly, an increasing number of studies have explored structural brain factors and functional connectivity in monolingual vs. bilingual brains, taking into account factors like AoA and language use (e.g., Gullifer et al., 2018; Mecchelli et al. 2004; see Pliatsikas, 2019 for a recent review). These studies have documented high brain plasticity related to life-long experiential factors. Many studies measure differences in functional connectivity between early and late bilinguals, early bilinguals showing for instance higher connectivity between the left and the right IFG, considered as key areas in bilingual language control (e.g., Gullifer et al., 2018). This advantage seems to be moderated later on by on-going experience with the languages (Sulpizio et al., 2020), in accordance with the Adaptive Control Hypothesis (Green & Abutalebi, 2013).

While a general picture about control processes involved in bilingual language processing emerges from these findings, it is not yet clear how exactly these are modulated by experiential factors, which vary among and within different bilingual or multilingual populations (e.g., Bonfieni et al., 2019; Sulpizio et al. 2020). Hence, more data with bilinguals and multilinguals from different linguistic and social settings are needed in order to get a clearer picture, and additional efforts have to be made in order to operationalize the variables related to experience. While proficiency is hypothesized to have a strong influence on neurocognition of bilingualism (e.g., following the Convergence Hypothesis, Green, 2003), namely in its potential to

modulate AoA effects, most studies rely only on subjective indicators such as self-assessment. Moreover, it is generally supposed the first acquired language remains the language the subject is more proficient in, often qualified as the dominant language. In the present study, we define language proficiency as a complex measure based on Complexity, Accuracy and Fluency in a language following the CAF framework (Housen, Kuiken & Vedder, 2012) and take into account the dynamic interaction of the languages of a bilingual (e.g., Schmid & Köpke, 2017).

In addition, plasticity research shows that the neural patterns of L2 learning are often, if not always, accompanied by anatomical changes in brain structure (Li, Legault, & Litcofsky, 2014). Mårtensson et al. (2012) investigated L2 learning through intensive linguistic training, examining interpreters before language courses and after 3 months. Interpreters showed a larger cortical thickness in the left inferior, middle frontal, and left superior temporal gyri, and a higher hippocampal volume compared to controls. Moreover, changes in the right hippocampus and in left STG were found only in interpreters that easily achieved L2 learning, while those who struggled in L2 learning showed larger cortical thickness in the left IFG. These findings showed the influence of adult-language acquisition on structural changes in brain regions that are related to language functions.

Klein et al. (2014) examined the role of AoA in L2 learning in early simultaneous bilinguals (0-3 years), early sequential bilinguals (4-7 years) and late bilinguals (8-13 years) compared to monolinguals. No difference was found between monolinguals and early simultaneous bilinguals. But they observed greater thickness in the left IFG and lesser thickness in the right equivalent region in early sequential and late bilinguals compared to monolinguals. Moreover, they found a correlation between AoA and cortical thickness of the left-IFG: the later an L2 was acquired the thicker the cortex.

Hence, the aims of the study were:

- i) to examine whether neural correlates of the second language (L2) converge with the native language (L1) as predicted by Green (2003) when proficiency is carefully controlled for through performance measures;
- ii) to investigate whether life-long exposure to the task of negotiating between two languages has an effect on the neural network subserving language control i.e., the

dorsolateral prefrontal cortex, the supplementary motor area, the anterior cingulate cortex, the caudate and the cerebellum, in which activation would then be modulated by age of acquisition.

We also sought to identify grey matter anatomical differences in the brain regions involved in language processing and control in such highly proficient early and late bilinguals.

## Materials and Methods

The present study involved 20 highly proficient English-French bilinguals living in a French-speaking environment. We investigated their performance in a single-language and in a language switching picture naming task. In order to control for proficiency, participants performed various language tests, including a language assessment test, a picture naming task and a verbal fluency test in both languages before MRI scanning.

### Participants

Twenty French/English bilinguals took part in the experiment. All participants were highly proficient in both languages and did not speak any other languages. All participants affirmed using both French and English at least weekly. All early bilinguals, except one, were born in a family with each parent speaking one of the two languages. One early bilingual had two French speaking parents but spent his infancy in the US and had an English-speaking carer. The participants are described in Table 1. They were separated in two groups according to their AoA of L2: i) 10 early bilinguals who acquired both languages before 3 years old (L1 French 6, English 4; three females and seven males; mean age, 24.7, range 20-31) and ii) 10 late bilinguals having learned their L2 after age 10 (L1 French 5, English 5; 5 females and 5 males; mean age 28.7, range 24-40). The choice of these two languages was due to their typological relatedness: we did not expect any differences in processing of English and French, as both are Indo-European flexional languages sharing an important part of vocabulary roots and grammatical features. A near-equal balance between French and English as L1 (and naturally L2) was observed. Moreover, the participants were highly balanced and reported frequent



use of both languages. By L1, we refer to a participant's first acquired language in late bilinguals, and to the language spoken in the country of birth for the early bilinguals.

All participants were right-handed as assessed by the Edinburgh Inventory Scale (Oldfield, 1971). They had no history of neurological or psychological disorders. The study was approved by the French ethical committee of the CPP SOOM IV (Comité de Protection des Personnes Sud-Ouest & Outre-Mer IV). All participants had given informed written consent, and received a reward for their participation at the end of the study.

## Language assessment

During the week preceding the MR component of the experiment, participants completed a sociolinguistic questionnaire to establish their biography of language learning, use and proficiency of each language, followed by a language assessment test (the Efficient Language Assessment Online - ELAO), based on the Common European Framework of Reference (CEFR; North, 2000) providing a score out of 100. This test evaluates complexity and accuracy of vocabulary and grammatical skills in comprehension. In addition, in order to assess production skills and fluency, participants underwent a verbal fluency test (letter and category fluency; Cardebat, Doyon, Puel, Goulet & Joannette, 1990; Strauss, Sherman & Spreen, 2006) and a picture naming task (involving material with the same characteristics as that used for the experimental task, but not the same stimulus objects to identify) in both languages (Glaser, 1992).

On the ELAO all participants obtained C1 or C2 level in both languages and no difference was found between the two groups, neither in L1 (early: mean  $88.9 \pm 5.8$ , late: mean  $92. \pm 3.1$ ,  $U=50.0$ ,  $p=1.0$ ) nor L2 (early: mean  $87.0 \pm 5.2$ , late: mean  $85.0 \pm 5.1$ ,  $U=35.0$ ,  $p=0.280$ ). Mann-Whitney U analyses (to test sampling equivalence in ordinal data) with proficiency test performance as input did not show any significant differences between early and late bilinguals: verbal fluency tests in L1 (phonemic fluency,  $U=28.0$ ,  $p=0.105$ ; semantic fluency,  $U=32.5$ ,  $p=0.190$ ), in L2 (phonemic fluency,  $U=41.0$ ,  $p=0.529$ ; semantic fluency,  $U=39.0$ ,  $p=0.436$ ) and picture naming test (accuracy score: L1,  $U=50.0$ ,  $p=1.0$ ; L2,  $U=43.0$ ,  $p=0.631$ ; switch,  $U=34.0$ ,  $p=0.247$ ). The participants underwent also a number of

neuropsychological measures (Stroop, WAIS, TMT, MMSE) and no differences between the early and late bilingual groups occurred.

## fMRI Study Design

The fMRI experimental design consisted of 6 runs, each run lasting approximately 6 minutes, where all conditions were presented in a pseudo-random order (not entirely random, in order to be sure of equal group sizes). Across all subjects, the order of presentation of the 6 runs was balanced for L1 / L2.

Each run was further divided into 12 activation blocks, during which all conditions were presented in a pseudo-random order. Each block was followed by a rest period of 8850 ms (2950 x 3 ms), during which a fixation cross was presented and subjects were instructed to rest.

For the picture naming task, 168 black and white drawings were selected from the Centre for Research in Language-International Picture Naming Project corpus CRL-IPNP (Szekely et al., 2005). For information on frequency, name agreement and image agreement we referred to Alario & Ferrand (1999) for French, and Szekely et al. (2005) for English. Mean name agreement for the two languages was 91.1% for French and 92.1% for English. Mean word length was 1.3 syllables in English and 1.7 in French. Mean picture familiarity for French was 3.1 and for English 3.4 on a scale from 1 to 5. Frequency was controlled with the values given by Alario & Ferrand (1999) for French (based on the Brulex database) and on the CELEX efreq based on a logarithmic transformation used in the CRL-IPNP for English. Half of the items were high-frequency words (mean 70.6 for French and 4.2 for English) and the other half were low-frequency words (mean 26.7 for French and 2.1 for English). In total, each participant was presented with 504 stimuli: 168 images named in each of the three conditions: L1, L2 and switched.

In the switched condition, the cue alternated every trial between one language and the other. As an alternative to random language switching, this predictability prevents a confound with the blocked condition, in which language is of course predictable. A similar paradigm was already used in Hernandez et al (2001) with the difference that in our study participants were instructed to name pictures aloud in order that their responses could be collected and analysed for reaction time.

In each activation block 7 pictures were presented, one every 2950ms. The picture was preceded by a visual language cue for 450ms, then displayed for 1500ms, followed by a fixation cross for 1000ms. The language cue, comprising the English word “say” or the French word “dire”, instructed the participant about the language of response.

## MRI Data Acquisition and Analysis

For each participant, the experiment was conducted in a single session lasting approximately 1 hour, using a Philips ACHIEVA (3 Tesla) MRI scanner equipped with an 8-channels SENSE head coil. Visual presentation was provided by a Toshiba video projector back-project on a transparent screen. Participants were fitted with a MR CONFON headphone and earplug as a protection from MRI noise.

Before the fMRI task, a high resolution 3D anatomical image of the entire brain was acquired, composed of 170 T<sub>1</sub>-weighted images ( $T_R = 8,1\text{ms}$ ;  $T_E = 3.7\text{ms}$ ; flip angle =  $8^\circ$ ; field of view (FoV) =  $240 \times 240\text{ mm}$ ; voxel size =  $1\text{ mm}^3$ ). Functional images were acquired using a T<sub>2</sub> echo-planar imaging (EPI) sequence ( $T_R = 2950\text{ms}$ ;  $T_E = 30\text{ms}$ ; flip angle =  $90^\circ$ ; field of view (FoV) =  $240 \times 240\text{ mm}$ ). Each functional image volume was composed of  $80 \times 80 \times 38$  voxels, each voxel being  $3 \times 3 \times 3\text{ mm}$ .

The data were processed and analysed using Statistical Parametric Mapping (SPM12; (<http://www.fil.ion.ucl.ac.uk/spm>; Wellcome Department of Cognitive Neurology, London, UK), running on Matlab 8.6 (MathWorks, Natick, MA). Slice-timing procedures were applied to all EPI images to correct for differences in acquisition time between slices. Functional images of each subject were realigned to correct for movements, co-registered to the structural image, normalized into Montreal Neurological Institute (MNI) stereotactic space and smoothed by a 6mm isotropic Gaussian kernel. At first level, single subjects' data were analysed with a fixed effects model within the framework of the General Linear Model (Friston, et al., 1995). The six motion parameters derived from realignment stage were included in the model as regressor of no interest. The group averaged effects were computed with a random-effects model.

Three simple main conditions were tested: naming in L1 (blocked trials); naming in L2 (blocked trials); and naming alternately L1 and L2 (switched trials). Whole-brain contrast t-tests, comparing statistical maps between three conditions, were

conducted using a threshold of  $p < 0.05$  voxel-wise corrected using Family Wise Error (FWE) correction, with an extent threshold of 100 contiguous voxels. When no activation was found we employed a statistical threshold of  $p < 0.001$ , uncorrected for multiple comparisons, with an extent threshold of 100 contiguous voxels. The anatomical location of significant clusters was determined with xjView 8 toolbox for SPM (<http://www.alivelearn.net/xjview8>, Cui, Li, & Song, 2011). Figures were created using MRICron software (Rorden & Brett, 2001).

## Cortical Thickness

We measured cortical thickness to detect anatomical differences among late and early bilinguals. An automatic measurement was performed on MRI 3D T1 images using Corthizon (Querbes, 2009). Corthizon is a MATLAB toolbox which estimates the individual cortical thickness of each subject using a Laplace-based technique. Corthizon provided a measurement of cortical thickness across the entire brain excluding cerebellum at over 45 Brodmann areas (left and right hemisphere) and 90 gyri. Normalization of cortical thickness was performed over all participants by dividing each participant's area score by the whole brain cortical thickness mean of the participant.

## Results

### Behavioural Results

Analyses were performed on corrected naming latencies, after eliminating errors and outliers (3 SD above or below the mean for each participant; 2.5% of total data).

Mean response times are given in Table 2, showing the similarity of results between conditions. We conducted a repeated-measures ANOVA with "condition" (blocked and switched) and "language" (L1 and L2) as within-subject factors and "AoA" (early vs. late bilinguals) as a between-subjects factor.

Only a condition effect was found: switch trials were slower than blocked trials [ $F(1,17)=34.804$ ,  $p=0.000$ ]. No AoA effect was found [ $F(1,17)=0.062$ ,  $p=0.80$ ]. The interaction between condition and language [ $F(1,17)=1.47$ ,  $p=0.24$ ] was not significant as well as the "condition"  $\times$  "language"  $\times$

“group” interaction [ $F(1,17)=1.30$ ,  $p=0.27$ ]. These results indicate no overall difference between the groups in mean response times.

## Functional Neuroimaging Results

### Language Network

Functional neuroimaging analysis of all participants showed areas of brain activity common to picture naming in both the blocked and the switched naming conditions (Figure 1). Table 3 describes the regional activations in the switched as compared to the blocked condition. Overall, bilateral activity was present in the visual cortex (BA 17, 18, 19), the fusiform gyrus (BA 37), the dorsolateral premotor area (BA 6), the postcentral gyrus (BA 4), the superior parietal lobule (BA 7), the superior temporal cortex (BA 21/22), the posterior inferior temporal gyrus (IFG, BA 20), the anterior cingulate cortex (ACC, BA 32), and cerebellum.

### Blocked Condition

Activity in the Supplementary Motor Area (medial BA 6) was more extended in the left hemisphere for both L1 and L2 blocked naming conditions. This network has already been identified as involved in word production for picture naming (Indefrey, 2011) including the Inferior Frontal Gyrus, the posterior parts of the superior temporal gyrus, the SMA, the fusiform gyrus and the cerebellum. Activity in precentral and postcentral gyri are associated with articulatory processing (Hillis et al, 2004) and assumed to reflect the retrieval of phonological representations in overt naming (Murtha, Chertkow, Beauregard & Evans, 1999). The superior parietal lobule has been related to semantic processing (Wong, Yin & O'Brien, 2016).

Notably, activation in the left thalamus was only observed for naming in L1, while in L2 an additional left-lateralized neuronal activity was observed in the IFG (Broca's area; BA 44/45) and in the anterior insula. The role of the thalamus in verbal memory processing concerns cortical activation and mediation of sensor input (van Lieshout, Renier, Eling, de Bot, & Slis, 1990). The processes in which the IFG and insula are activated include some involved with language and working memory (Chee, Soon, Lee, & Pallier, 2004; Poldrack, et al., 1999) while Chee et al. (2004) also refers to the participation of areas traditionally associated with motor function.

Neither was any activation difference found in the direct comparison between early and late bilinguals. Hence, our results reinforce the hypothesis that the representations of both languages converge once high proficiency is reached, irrespective of AoA. Other functional neuroimaging studies have reported similar activations in frontal and temporoparietal areas in balanced bilingual speakers (Chee et al, 1999; Hernandez et al, 2000, 2001; Perani et al, 2003). This suggests that proficiency rather than AoA exerts influence on language representation.

### Switched Condition

The switched condition compared to the baseline revealed a similar pattern of brain activity, namely the bilateral precentral gyrus (BA 6), the SMA and the ACC (BA 32), the superior temporal gyrus (BA 22), the posterior inferior temporal gyrus (BA 20), the fusiform gyrus (BA 37) and the occipital lobe (BA 17, 18, 19), the thalamus and the cerebellum (fig. 1).

The comparison between switched and blocked conditions revealed increased activity during the switched tasks in the bilateral inferior and superior parietal lobule (BA 40/7), the left precentral gyrus (BA 6), the left middle frontal gyrus, and middle cingulate cortex (BA 24/32; see Fig. 2 and Table 3). No additional specific activation was found in the reverse comparison (blocked compared to switched).

### Cortical thickness

Cortical thickness contrasts of early bilinguals compared to late bilingual showed differences in two Brodmann areas. The area 45 right (Broca's area) was significantly thicker in early bilingual group (0.86mm) compare to late bilingual group [0.79mm;  $t(18)=-2.681$ ,  $p=0.01$ ]. The same pattern was found for area 38 left, the most rostral portion of the STG and the middle temporal gyrus, known as the temporal pole (early: 1.25mm; late 1.15mm,  $t(18)=2.103$ ,  $p=0.05$ ).

## Discussion

The aim of this study was to identify possible differences in the neural correlates and language control brain network, between two groups of highly proficient bilinguals, one with two languages since early life and the other which had acquired their

second language in adolescence. We found similar representation for L1 and L2 and activation of a general executive network for the switch task. We did not find any difference between early and late bilinguals.

## Language Control Network

In this present study, we did not find any asymmetrical switch cost, even in the late bilingual group, suggesting that even if an L2 is acquired later in life, speakers with high proficiency overcome asymmetry in inhibitory resources required to control language selection.

Rather than interpreting this as evidence of a difference in mechanisms between high- and low-proficiency bilinguals, we prefer to suggest that at high proficiency, AoA becomes insignificant.

Direct comparison was conducted between switched and blocked naming conditions. At the behavioural level, slower response times were found in the switched condition. These findings are in line with previous studies showing a language context effect and suggesting a switch cost when alternating between languages (Costa & Santesteban, 2004). The magnitude of the switch cost is also interesting: it varies depending on the difficulty of the task. For instance, switching from the non-dominant to the dominant language entails larger switch costs due to the speaker exerting stronger inhibition of the dominant language when processing the non-dominant one (Meuter & Allport, 1999). This pattern is not observed in highly proficient bilinguals since there is no difference in proficiency between the two languages. Hence, an equal effort is required to inhibit either language. Moreover, in highly proficient bilinguals, such effects have also been observed when switching to a third low-proficient language (Costa, Santesteban & Ivanova, 2006). These results are challenging for the Inhibitory Control model, which predicts asymmetrical switching costs. In order to explain this discrepancy, it has been suggested that once a certain level of proficiency is attained in both languages, a mechanism specific to language control, not relying on domain-general inhibition, is used to overcome lexical competition (Calabria, Hernandez, Branzi & Costa, 2012).

Two alternative hypotheses have been advanced regarding the nature of such a language control mechanism (Abutalebi & Green, 2007). First, it is proposed that language control is completely subsidiary to domain-general executive control

functioning, i.e. language control will recruit the same set of executive control processes as involved in non-linguistic task switching for instance. Another hypothesis is that this mechanism is only partially subsidiary to the domain-general executive control, since daily use of languages in bilingual speakers leads to the development of control processes specific to language (Costa & Santesteban, 2004). At the brain level, the switched condition compared to the blocked condition revealed increased activity in a network including the left precentral gyrus, middle frontal gyrus, ACC, bilateral precuneus and the inferior parietal lobules. This pattern of activation has already been identified as indicating a network involved in cognitive control, and specifically in inhibition (Wager et al, 2005).

The DLPFC and the ACC are two regions that play a predominant role in cognitive control. In particular, activation of the DLPFC has been reported in tasks in which selection of the target stimulus is required for overcoming the preponderant irrelevant response (Heidlmayr, Doré-Mazars, Aparicio & Isel, 2016; Hernandez, 2009; Khateb et al, 2007; Lubrano, Prod'homme, Démonet & Köpke, 2012; Wang et al, 2009), and the ACC is a crucial region associated with error detection and conflict monitoring (Collette & Salmon, 2014, Fabbro, Skrap & Aglioti, 2000). Previous studies observed that these two regions are co-activated in conflict tasks and play a major role in selection of different response alternatives, task switching, maintaining a stable representation of the current task and inhibition of irrelevant items held in working memory (Rodriguez-Fornells, de Diego Balaguer & Münte, 2006). Studies have tried to dissociate their roles: the ACC seems to be responsible for the evaluation of the demand of cognitive control and the transmission of the need for greater control to the prefrontal cortex. The inferior and superior parietal lobules have been related to language selection in studies on language control (Abutalebi & Green, 2007; Hernandez, 2009) and to distinct executive functions as inhibition, flexibility and working memory (Niendam et al, 2012). Activation of the precuneus has been found in other language switching studies (Guo, Liu, Misra & Kroll, 2011; Wang et al, 2007) and has been linked to response inhibition (Bunge, Dudukovic, Thomason, Vaidya & Gabrielli, 2002) but its precise role has not been clarified (de Bruin, Roelofs, Dijkstra & FitzPatrick, 2014).

Our results showed that simultaneous bilinguals display thicker right IFG than late bilinguals. This was also observed by Klein et al. (2014) and supports the suggestion that AoA shapes the structure of the brain. The changes in the inferior frontal cortex



in our study might reflect different learning processes associated with implicit and explicit language learning. Our evidence is consistent with the findings of Hull and Vaid (2007) that showed that bilinguals who acquired both languages by six years of age showed involvement of both hemispheres for both languages, whereas those who acquired their second language after age six showed left hemisphere dominance for both languages.

We also observe a plasticity effect associated with L2 AoA in the left temporal pole: thicker cortex in early bilinguals than in late bilinguals. This region has already been found to be thicker in bilinguals compared to monolinguals in the study of Abutalebi and colleagues (2014). And it is known to be involved in the storage of lexical concepts and in the separation of these lexical concepts in two languages in order to guide speech production and comprehension processes (Abutalebi et al., 2014). A possible interpretation is that this structure is a potential target for plastic changes in early bilinguals because it must be recruited early to guide word production in each language of the bilingual speaker.

Though we do not presume to answer delicate questions on cortical thickness with these data, the inclusion of thickness data provides some reassurance over our sample size. While obviously small and therefore limiting, necessarily due to the recruitment only of high proficiency participants, our sample proved sufficient to observe a plasticity effect.

Taken together, our results show that switching between languages in highly proficient bilinguals involves an increase in areas reported as components associated with inhibitory processes. While our results have to be taken with caution due to the small number of participants in each group ( $n=10$ ), they suggest that language switching in proficient bilinguals recruits a neural network that is engaged for domain-general executive control functions rather than a specific language system. Moreover, the lack of differences between the two groups could indicate that when bilinguals reach a high level of proficiency in both languages, they use the same neural network in language production and control regardless of AoA.

The aim of this study was to look for functional and structural differences in the neural correlates of language processing and control in highly proficient bilinguals that could be driven by the age of acquisition of L2. Using fMRI, we found similar patterns of activations for L1 and L2 processing, and an enhanced general executive network for switching between two languages. We did not find any difference in brain

activations between early and late bilinguals, although structural differences in the grey matter have been elicited in the fronto-temporal cortex.

## Compliance with Ethical Standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (CPP13-025/2013-A01155-40) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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## Tables and Figures

Table 1a. Details of participants in early and late bilingual groups. ELAO is the result of the Efficient Language Assessment Online test.

Subject	Age	Gender	L1	L2	L2 AoA	L1 ELAO	L2 ELAO
Early							
1	31	F	Eng	Fr	< 3	C 1	C 1
2	22	M	Fr	Eng	< 3	C 1	C 1
3	27	F	Eng	Fr	< 3	C 1	C 1
4	22	M	Fr	Eng	< 3	C 1	C 1
5	22	F	Eng	Fr	< 3	C 2	C 2
6	20	M	Eng	Fr	< 3	C 1	C 1
7	27	M	Fr	Eng	< 3	C 2	C 2
8	26	M	Fr	Eng	< 3	C 2	C 2
9	26	M	Fr	Eng	< 3	C 2	C 2
10	24	M	Fr	Eng	< 3	C 1	C 1
Late							
1	25	M	Fr	Eng	11	C 1	C 2
2	24	F	Eng	Fr	11	C 2	C 2
3	29	M	Fr	Eng	12	C 2	C 1
4	23	F	Eng	Fr	10	C 2	C 1
5	24	F	Eng	Fr	10	C 2	C 1
6	34	M	Fr	Eng	10	C 2	C 1
7	23	M	Eng	Fr	10	C 1	C 1
8	36	F	Eng	Fr	11	C 1	C 1

9	40	M	Fr	Eng	14	C 2	C 1
10	29	F	Fr	Eng	11	C 2	C 1

Table 1b. Group characteristics and mean language scores.

	Early Bilinguals	Late Bilinguals	Significance (p)
Age	24.7±3.3	28.7±6.0	ns
Gender	3(f) / 7(m)	5(f)/5(m)	-
AoA L2	0**	11±1.2**	0.001
L1 French/English	6 (F)/ 4(E)	5(F)/4(E)	ns
L2 French/English	4(E)/ 6(F)	4(F)/5(E)	ns
L1 proficiency	88.9±5.8	92±3.1	ns
L2 proficiency	87±5.2	85±4.7	ns
L1 Phonemic Fluency test	14.4±5.1	18.1±3.9	ns
L2 Phonemic Fluency test	13.5±2.5	14.6±2.0	ns
L1 Semantic Fluency test	22.2±4.3	25.3±6.3	ns
L2 Semantic Fluency test	21.1±5.2	22.3±5.6	ns
Picture naming task - L1	49.6±0.8	49.3±1.6	ns
Picture naming task – L2	48.4±1.2	48.3±1.5	ns
Picture naming task - switch	96.4±2.5	97.8±1.9	ns

Table 2. Response time means of each group in the 3 conditions: L1 naming, L2 naming and switch naming condition. Standard error in brackets.

RT (ms)	Early bilinguals		Late Bilinguals		Total	
	L1	L2	L1	L2	L1	L2
Blocked	988 (05)	1000 (04)	994 (09)	996 (05)	991 (08)	998 (04)

Switch	1039 (06)	1021 (05)		1041 (08)	1042 (06)		1040 (07)	1031 (05)
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Fig. 1: Brain areas that show greater activation for L1 (left), L2 (centre) and switch (right) naming tasks compared to the baseline in early and late bilinguals (n=20) performing the picture naming task at  $p < 0.05$  corrected,  $k = 100$ .

Fig. 2: Brain areas that show greater activation for switch naming compared to the blocked condition in early and late bilinguals (n=20) performing the picture naming task at  $p < 0.001$  uncorrected,  $k = 100$ .

Table 3. Areas of increased activity for switched compared to blocked condition in proficient bilinguals (N=20).

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
L Inferior Parietal Lobule (BA 40)	376	6,802	-30	-46	47
L Precuneus (BA7)		6,462	-15	-58	53
R Precuneus (BA7)		5,627	6	-55	50
R Inferior Parietal Lobule (BA 40)	134	5,666	30	-49	47
L Middle Frontal Gyrus (BA 6)	129	5,484	-24	-7	47

L ACC (BA 24/32)	5,13	-12	5	47
L Precentral Gyrus (BA 6)	4,184	-48	5	44

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# Annexe : Results of fMRI tasks.

**L1 compared to baseline in all 20 participants (p<.05, FEW corr., k > 100)**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus (BA 19/18)	3047	17,318	27	-91	8
L Fusiform Gyrus (BA 37)		14,016	-39	-40	-16
L Middle Occipital Gyrus (BA 19/18)		13,777	-45	-67	-7
L Thalamus	267	12,450	-24	-34	8
L Putamen		7,367	-18	-7	8
L Precentral Gyrus (BA 6)	440	12,110	-48	-10	32
L Postcentral Gyrus (BA 4)		10,621	-57	-13	14
L Superior Temporal Gyrus (BA 22)		7,978	-60	-37	8
R Precentral Gyrus (BA 6)	389	11,864	54	-10	26
R Superior Temporal Gyrus (BA 22)		10,412	63	-7	2
		8,762	54	-34	8
L SMA (BA 6)	201	10,384	-3	5	56
R MCC (BA 32)		9,853	9	17	44

**L2 compared to baseline in all participants ( $p < .05$ , FEW corr.,  $k > 100$ )**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus (BA 19/18)	3012	18,713	27	-91	8
R Fusiform Gyrus (BA 37)		15,323	36	-64	-13
L Fusiform Gyrus (BA 37)		14,592	-39	-40	-16
L Insula Lobe (BA 13)	100	13,537	-33	14	2
		10,59	-27	29	-1
L Precentral Gyrus (BA 6)	451	12,266	-45	-4	47
L Superior Temporal Gyrus (BA 22)		11,300	-54	-16	5
L Postcentral Gyrus (BA 4)		8,783	-48	-7	23
R Precentral Gyrus (BA 6)	223	11,370	45	-13	35
R Postcentral Gyrus (BA 43)		9,502	63	-7	20
R Precentral Gyrus (BA 6)		6,740	48	2	50
L IFG (p. Opercularis) (BA 44)	108	11,109	-51	11	23
L Insula Lobe (BA 13)		9,116	-30	8	20
L SMA (BA 6)	243	10,896	-3	5	56
R MCC (BA 32)		9,650	9	17	44
L MCC (BA 32)		7,463	-9	20	32
R Superior Temporal Gyrus (BA 22)	164	9,831	60	-25	5

R Middle Temporal Gyrus (BA 21)		8,173	60	-1	-4
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**Switching compared to baseline in all participants ( $p < .05$ , FEW corr.,  $k > 100$ )**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus (BA 19/18)	3317	18,018	27	-91	8
R Fusiform Gyrus (BA 37)		14,861	36	-61	-13
L Cuneus (BA 17)		14,703	-12	-97	-7
L Precentral Gyrus (BA 6)	455	12,234	-45	-13	32
L Superior Temporal Gyrus (BA 22)		11,637	-54	-16	5
		8,863	-60	-37	8
R Precentral Gyrus (BA 6)	391	11,951	54	-10	26
R Superior Temporal Gyrus (BA 22)		10,991	63	-7	2
		8,814	51	-34	8
L SMA (BA 6)	230	10,034	-3	2	59
R MCC (BA 32)		8,811	9	17	44



**L1 compared to baseline in early bilinguals (p<.001, no corr., k > 100)**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
L Postcentral Gyrus	6873	18,476	-57	-13	14
R Middle Occipital Gyrus	6873	17,592	24	-94	11
R Hippocampus	6873	16,051	30	-34	-1
R Postcentral Gyrus (BA3)	236	12,495	9	-34	62
R Precentral Gyrus	236	11,99	15	-25	77
L Postcentral Gyrus (BA5)	236	6,986	-6	-46	68
L ACC (BA32)	532	9,886	-3	17	35
L Medial Frontal Gyrus (BA6)	532	9,533	-12	5	53
L SMA (BA6)	532	7,835	-6	-4	71
R Precentral Gyrus	742	9,263	57	-7	29
R Superior Temporal Gyrus	742	8,998	54	8	-4
R Superior Temporal Gyrus	742	7,744	54	-13	2

**L2 compared to baseline in early bilinguals (p<.001, no corr., k > 100)**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus	7303	18,058	24	-94	11
L Culmen	7303	17,037	-3	-64	-16
L Fusiform gyrus	7303	12.93	-39	-40	-16
R Superior Temporal Gyrus (BA22)	294	10,708	63	-7	-1
R Superior Temporal Gyrus (BA22)	294	7,628	63	-28	5
R Superior Temporal Gyrus (BA38)	294	6,285	54	11	-16
R MCC (BA32)	552	10,448	12	17	44
L SMA (BA6)	552	9,588	-12	5	53
R SMA (BA6)	552	8,361	12	-1	62
R Precentral Gyrus (BA 6)	387	9,818	48	-7	26
R Precentral Gyrus	387	7,908	57	-7	44
R Precuneus	387	6,227	30	-7	38
R IFG (p. Triangularis)	145	6.98	33	29	2
R Middle Frontal Gyrus	145	4,91	30	38	-4
R IFG (p. Orbitalis)	145	4,908	42	23	-10
R IFG (p. Opercularis)	101	7,986	42	14	17
R Middle Frontal Gyrus (BA9)	101	4.78	51	14	32

**Switch condition compared to baseline in early bilinguals ( $p < .001$ , no corr.,  $k > 100$ )**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus	9832	20,809	24	-94	11
L Culmen	9832	14.97	-27	-58	-25
R Superior Temporal Gyrus	9832	13.80	60	-7	-1
R Postcentral Gyrus (BA3)	132	10,670	6	-34	65
R Insula Lobe	138	7,518	33	17	2
R IFG (p. Orbitalis)	138	6.72	39	29	-7

**L1 compared to baseline in late bilinguals ( $p < .001$ , no corr.,  $k > 100$ )**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus(BA 18/19)	5368	13,982	24	-94	8
L Middle Occipital Gyrus(BA 18/19)	5368	13,103	-18	-94	5
R Precuneus (BA7)	5368	10.59	27	-73	38
R Precentral Gyrus (BA6)	645	12,013	42	-10	44
R Superior Temporal Gyrus	645	10,279	57	-37	5
R Superior Temporal Gyrus	645	8,712	63	-7	8
R Thalamus	119	8,572	24	-31	5
R SMA(BA6)	218	8,150	12	11	71
L SMA (BA6)	218	7,916	-6	8	56
R ACC (BA 32)	218	5,606	9	17	44

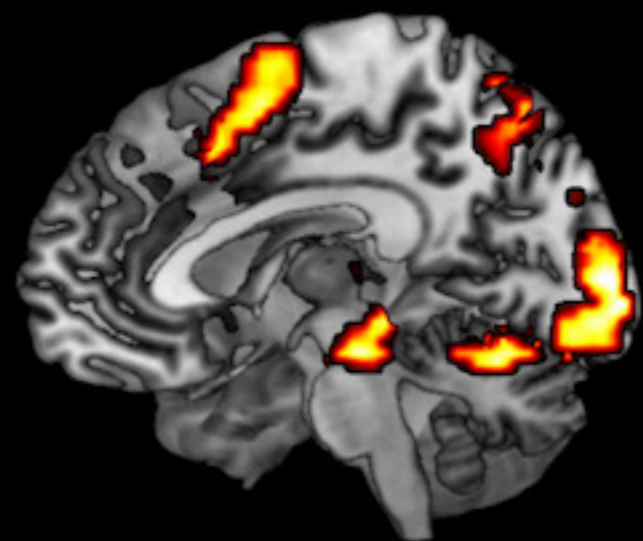
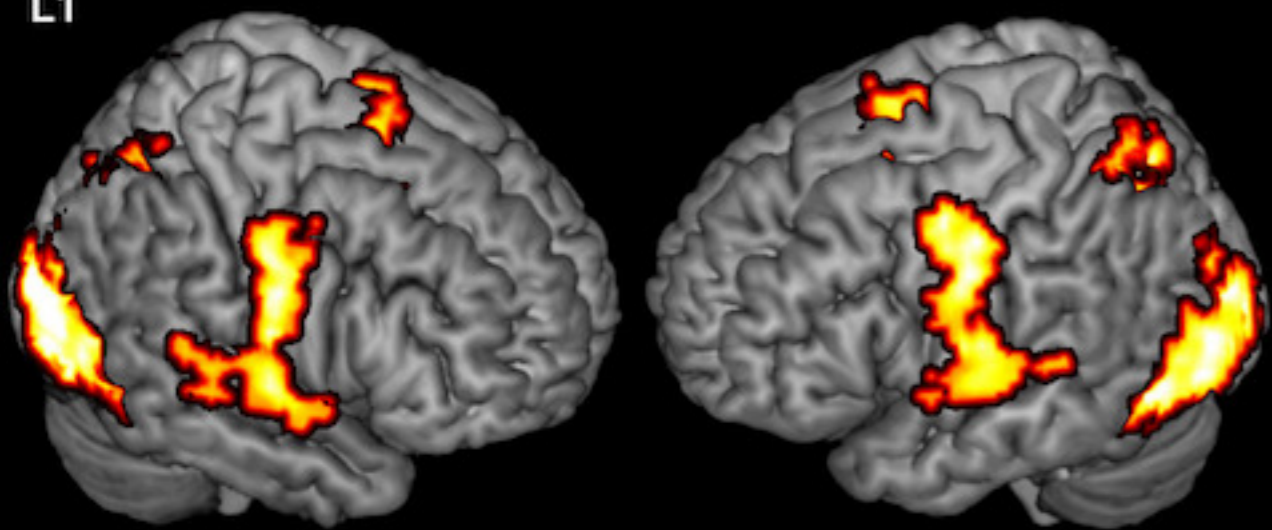
**L2 compared to baseline in late bilinguals ( $p < .001$ , no corr.,  $k > 100$ )**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Middle Occipital Gyrus	4124	14,899	27	-91	8
R Fusiform Gyrus	4124	13,098	42	-52	-16
R Fusiform Gyrus	4124	11,752	27	-64	-10
L Insula Lobe	209	13,490	-36	8	2
L ACC	209	9,794	-15	29	-1
R Precentral Gyrus	550	12,143	42	-10	44
R Middle Temporal Gyrus (BA22)	550	9,224	60	-34	2
R Precentral Gyrus (BA6)	550	7,229	54	-10	26
R Globus Pallidus	130	11,744	21	-13	-1
R Thalamus	130	8,241	24	-31	14
L IFG (p. Opercularis)	619	11,603	-51	8	26
L Precentral Gyrus	619	9,885	-48	-10	38
L Postcentral Gyrus (BA43)	619	6,894	-60	-7	14
R SMA (BA6)	275	8,709	12	11	71
L SMA (BA6)	275	7,809	-6	8	56
L ACC (BA32)	275	5,608	-9	20	32

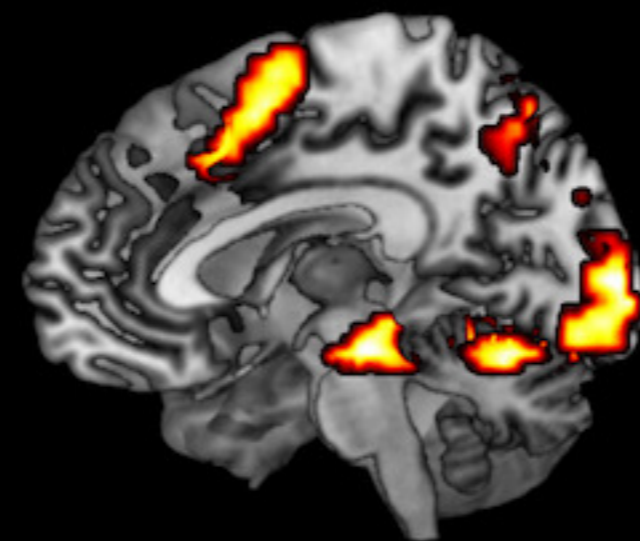
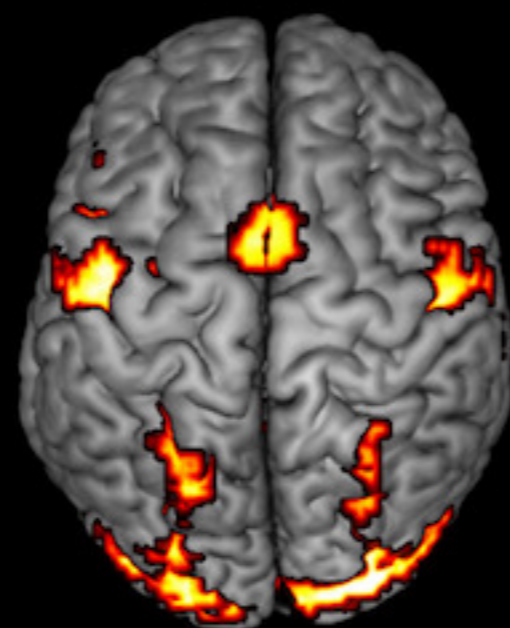
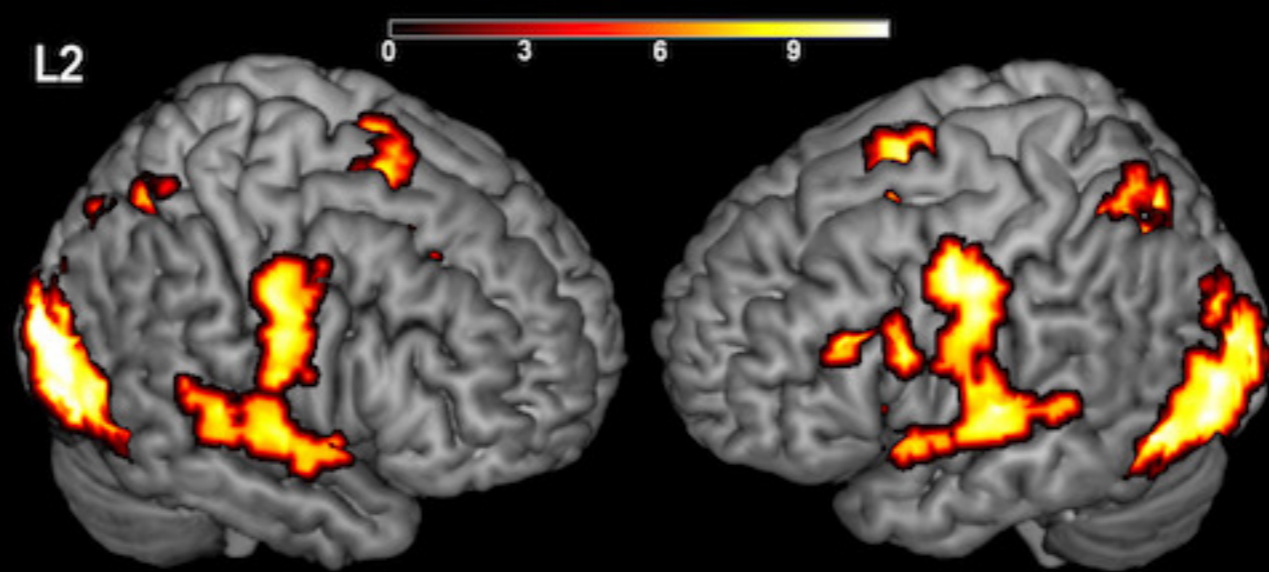
**Switching compared to baseline in late bilinguals (p<.001, no corr., k > 100)**

Region Label	Extent	t-value	MNI Coordinates		
			x	y	z
R Fusiform Gyrus	4169	14,695	27	-64	-10
R Middle Occipital Gyrus	4169	14,061	27	-91	8
L Middle Occipital Gyrus	4169	12,372	-48	-67	-7
R Superior Temporal Gyrus	526	12,719	57	-37	5
R Precentral Gyrus	526	10,563	39	-10	41
R Precentral Gyrus	526	7,811	54	-10	26
L Precentral Gyrus	667	9,503	-48	-10	38
L IFG (p. Opercularis)	667	8,838	-51	8	26
L SMA (BA6)	229	8,128	-6	8	56
R SMA (BA6)	229	8,011	12	11	71

L1



L2



S

