Language Control in Bilinguals: Monitoring and Response Selection

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Abstract

Language control refers to the cognitive mechanism that allows bilinguals to correctly speak in one language avoiding interference from the nontarget language. Bilinguals achieve this feat by engaging brain areas closely related to cognitive control. However, 2 questions still await resolution: whether this network is differently engaged when controlling nonlinguistic representations, and whether this network is differently engaged when control is exerted upon a restricted set of lexical representations that were previously used (i.e., local control) as opposed to control of the entire language system (i.e., global control). In the present event-related functional magnetic resonance imaging study, we investigated these 2 questions by employing linguistic and nonlinguistic blocked switching tasks in the same bilingual participants. We first report that the left prefrontal cortex is driven similarly for control of linguistic and nonlinguistic representations, suggesting its domain-general role in the implementation of response selection. Second, we propose that language control in bilinguals is hierarchically organized with the dorsal anterior cingulate cortex/presupplementary motor area acting as the supervisory attentional system, recruited for increased monitoring demands such as local control in the second language. On the other hand, prefrontal, inferior parietal areas and the caudate would act as the response selection system, tailored for language selection for both local and global control.

Key words: bilingualism, cognitive control, fMRI, language control, response selection

Introduction

Language control refers to a set of cognitive abilities, which allows bilinguals to utter a word in the intended language, avoiding interference from the nontarget language (Abutalebi and Green 2007, 2008; Green and Abutalebi 2013). The cognitive processes underlying language control entail the intention to speak in a given language, selection of the target response (the word in the intended language), inhibition of words from the nontarget language, and monitoring speech for potential intrusions (viable candidate words in the other language) (Costa et al. 1999; Kroll, et al. 2006; Abutalebi and Green 2007), as well as language disengagement and engagement (i.e., stop speaking in one language and switching to another language; see Green and Abutalebi 2013).

According to a prominent neurocognitive model of bilingual language processing (Abutalebi and Green 2007, 2008; Green and Abutalebi 2013), the above-mentioned processes are orchestrated by a network of cortical and subcortical brain areas, tightly related to executive control. Chief among these areas is the dorsal anterior cingulate cortex/presupplementary motor area (dACC/pre-SMA) complex involved in monitoring potential conflicts between languages and detection of potential errors...
this paradigm, they all involve speakers using their 2 languages in different ways when controlling linguistic versus nonlinguistic representations. In other words, it needs to be established if different types of responses (i.e., linguistic vs. nonlinguistic responses) would differentially engage the neural regions involved in the language control network (e.g., Green 1986, 1998; Abutalebi and Green 2007, 2008). Hence, it is important to clarify that the focus of the present study is not on the neural overlap between the bilingual language control network and the domain-general control network. Rather, this study aims at exploring how the language control network is modulated when exerting control over linguistic and nonlinguistic representations.

The second question of the present study concerns the scope at which language control is exerted (see De Groot and Christoffels 2006). The issue here is whether language control acts at the level of the specific stimulus to be selected, such as a lexical item (i.e., local control), or rather acts upon the entire language system (i.e., global control). Likewise, from a neural perspective, are similar brain systems engaged for local and global control, and if yes, whether to the same degree when controlling specific language response (S-LR) bindings (i.e., local control) as compared with when engaging/disengaging the whole language set (S-LS) (i.e., global control)?

The majority of the studies that investigated the above-mentioned questions have relied upon the so-called “language-switching paradigm” (e.g., Meuter and Allport 1999; Christoffels et al. 2007; Garbin et al. 2011; Misra et al. 2012; Branzi et al. 2014). Despite differences between the specific instantiations of this paradigm, they all involve speakers using their 2 languages in such a way that is possible to measure the aftereffects of using one language on the subsequent use of the other language. These aftereffects are generally observable in the so-called “switch cost.” This “cost,” measurable in response times (RTs) and in neural effects, arises since switching between languages requires shifting between 2 different S-LR sets (e.g., Waszak et al. 2003). Therefore, switching requires time and cognitive effort to establish new S-LR bindings, by overcoming the binding established before. As to its neural counterpart, following the aforementioned neurocognitive model of bilingual language processing (Abutalebi and Green 2007, 2008; Green and Abutalebi 2013), during language switching the PFC would work together with the dACC/pre-SMA and the basal ganglia in order to achieve this new S-LR bindings and overcome potential interference from the bindings established before. Specifically, the dACC/pre-SMA would signal potential response conflicts to the PFC, that in turn would trigger control of the nontarget S-LR bindings through inhibition driven by LC. This is the loop (PFC-LC loop) that allows language planning and language selection in the intended language.

The first aim of the present study is to assess whether this language control network is similarly involved when applying control processes over linguistic and nonlinguistic representations. This is a novel exploration, since the few existing studies have focused mostly on single areas of the language control system (e.g., the dACC/pre-SMA; see Abutalebi et al. 2012) and not on the functioning of an entire network of brain areas to determine the cortical overlap of language control and domain-general processes. Here, instead we focus on whether (and how) the cortical network related to language control is engaged also when control is applied over nonlinguistic representations. This will inform us also about the neural specificity of the language control network. In particular, we assess whether switching between S–R bindings modulate this network in the same manner, when such switching is performed over linguistic and nonlinguistic representations (e.g., Green 1986, 1998; Abutalebi and Green 2007, 2008; Green and Abutalebi 2013). In detail, changes of brain activity will be investigated during linguistic and nonlinguistic task performance by exploring neural “repetition priming” and “priming disruption” effects (e.g., Dobbins et al. 2004). Behaviorally, “repetition priming” effect refers to the faster RTs observed for the second repetition of the very same item (e.g., picture of a DOG, produce the word “dog”). This behavioral effect is accompanied by a decrease of neural responses for repeated stimuli in areas related to the stimulus processing (i.e., neural repetition priming or repetition suppression). This effect seems to reveal the reinforcement of S–R bindings set in the previous presentation of the stimulus (e.g., Stimulus: Picture/Response: Classification of the picture according to a semantic criteria A) (see Dobbins et al. 2004). Interestingly, however, when the same stimulus is repeated, but the task to be performed is not the same as previously conducted (e.g., Stimulus: Picture/Response: Classification of the picture according to a semantic criteria B), there is a disruption of neural priming (i.e., “priming disruption effect”). In other words, changing the task at hand disrupts neural priming (e.g., Dobbins et al. 2004). In the present study, we take the “neural priming disruption” effect as a measure of the control of S–R bindings in 2 distinct tasks (a semantic classification task with 2 different criteria and a language naming task with 2 different languages). This measure may be referred to as local control. Hence, we will assess differential local control effects between different tasks in brain areas associated to language control in bilinguals. Previously, the presence of local control effects has been taken to reflect that stimulus repetition automatically retrieves the task set previously associated with that stimulus, which can interfere with the establishment of any new task-set. Hence, “priming disruption” most likely is a consequence of an increased necessity to engage cognitive control resources in order to remap the new S–R bindings (Stimulus: Picture; Response: Semantic classification of the picture according to criteria B, according to the previous example) and reject the one used when performing the previous task (Stimulus: Picture; Response: Semantic classification of the picture according to criteria A) (e.g., Henson and Rugg 2003; Dobbins et al. 2004; Wig et al. 2009; Henson et al. 2014). Noteworthy, among other brain areas, the PFC has been found to be sensitive to the above described changes in the S–R bindings (e.g., Dobbins et al. 2004; Race et al. 2009), with priming effects “disrupted” in the PFC potentially revealing its key role in the control of S–R representations.
In the present investigation, we will compare changes of brain activity elicited when processing the same stimuli after and before either a linguistic or a semantic classification criteria change. We will assess this effect by measuring “priming disruption” in the brain [Note that in other studies (e.g., Dobbins et al., 2004), priming disruption effects have been measured differently than in the present study. In fact, priming disruption was measured by comparing new versus old items before and after the change of a task (see Dobbins et al., 2004)]. We expect a network of brain areas to be involved in a similar fashion in the control of S–R bindings between the linguistic task and the semantic classification task. That is, similar areas will be observed when changing languages and when changing semantic classification criteria.

However, to the extent to which S–R bindings may be established to different strength degrees, we may also expect control processes and their neural underpinnings to be entailed differently in contexts where a change of language or of semantic classification task occurs.

We expect therefore to observe differential changes in brain activity between the linguistic and the semantic classification task, in terms of increases or decreases of the measured blood–oxygen-level-dependent (BOLD) signal, in the same cortical and subcortical aforementioned areas, with a particular emphasis for the LPFC for the above-mentioned reasons (i.e., its key role in the control of S–R representations).

The second aim is more specifically related to language processing and refers to the involvement of the brain areas underlying local and global language control (De Groot and Christoffels 2006). As advanced earlier, local control refers to how a previous S–LR binding affects a successive S–LR remapping. In other words, local control refers to the aftereffects of naming a given picture in one language upon subsequent naming of that very same picture in the other language. On the other hand, global control refers to how the task instruction of naming in a given language (i.e., language A) affects subsequent performance when naming in the other language (i.e., language B), for stimuli that have not been previously used in language A. Presumably, the control exerted during language production in language A would subsequently affect the availability of any representations belonging to language B, regardless of whether these representations have been recalled or activated during the previous task.

Following some models of bilingual language processing, both control systems might be at play during bilingual language production (see De Groot and Christoffels 2006). Our aim is to explore how the language control network is recruited when applying these 2 sorts of control. In order to test local control effects we will assess changes of brain activity in the core areas proposed in the model by Abutalebi and Green (2007, 2008) (such as bilaterally the PFC, the LPFL, the RIPL, the LC, and the dACC/pre-SMA complex) elicited when processing the same stimuli after and before a linguistic task change. We will assess this effect by measuring “priming disruption” in the brain. Instead, to test global control effects we will assess changes of brain activity in the same brain areas elicited when processing new stimuli after and before a linguistic task change. This is also a novel aspect of our research. We would like to underline that a previous functional magnetic resonance imaging (fMRI) study attempted to investigate the neural differences between local and global control (Guo et al. 2011). However, this particular study was not carried out in a resolute fashion, primarily related to the way local and global control was defined and experimentally assessed. Indeed, Guo et al. (2011) assessed local and global control, by asking participants to switch between languages from trial to trial (mixed naming) or by asking participants to switch between languages on successive blocks of trials (blocked naming). The comparison between mixed versus blocked naming conditions was labeled as local control. Instead, the comparison between blocked conditions in each language was labeled as global control. These are highly interesting comparisons, however they probably speak more about sustained control than about global–local control, since only repeated pictures were employed in that study.

We think that a better way to study the functioning of global control is to contrast brain activity when performing a switch on items that have been previously named in the other language versus items that have not been named in that language before (see also De Groot and Christoffels 2006), for a similar theoretical approach. Hence, our study will directly answer the crucial question of how local and global control is processed neurally.

Importantly, for both questions addressed in this study we will consider the direction of the linguistic task change (i.e., from the first [L1] to the second language [L2] vs. from L2 to L1). This is because the aftereffects of naming in one language on the successive language may be different depending on the direction of language switch. At present we have little knowledge about how these aftereffects may depend on the language direction and on local or global control related issues. Further, since most studies have been conducted using electrophysiological measures (e.g., Misra et al. 2012; Branzi et al. 2014) the neural underpinnings of such effects are largely unknown. Addressing this issue by means of fMRI, may not only reveal the neural underpinnings of such processes but also lead, more generally, to a greater understanding of the complexity of language processing and control in the bilingual brain.

We expect to observe increased activity when passing from L2 to L1 than the reverse pattern. This is supposedly because language production in L2 might require a greater involvement of controlled processing (such as inhibiting the prepotent L1 during L2 production), as compared with L1 production, when associating each stimulus to its corresponding lexical candidate for the first time. Hence, it is possible that this extra-reinforcement of S-LR bindings in L2 will likely determine a greater effort in terms of control, when disengaging from the L2 S-LR bindings to establish new S-LR bindings for successive L1 production. Moreover, this L2 strengthening may be extended to the whole language set through a top-down controlled processing that would bias activation toward the correct language (see Runnqvist et al. 2012). Hence, if the whole L2 system is boosted the above-mentioned effects may be observed also for global control. In the case of the reverse order, that is, when going from L1 to L2, the outcome might be different, since L1 production as compared with L2 production might require less involvement of control areas when associating each stimulus to the lexical response and less control of interference from L2.

In summary, the purpose of the present fMRI study is 2-fold: to investigate whether the activity of the brain areas included in the language control network (e.g., Abutalebi and Green 2007; Green and Abutalebi 2013) is 1) modulated by the type of S–R bindings and whether it is 2) differentially engaged for local and global control in bilingual language production.

**Materials and Methods**

**Participants**

Eighteen high-proficient German/Italian bilingual volunteers took part in the experiment. Bilingual participants came from
Table 1 Language use and language proficiency

<table>
<thead>
<tr>
<th>Scale</th>
<th>L1 Language use</th>
<th>L2 Language use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preschool</td>
<td>0.9 (0.1)</td>
<td>0.2 (0.1)</td>
</tr>
<tr>
<td>Primary education</td>
<td>0.9 (0.1)</td>
<td>0.2 (0.1)</td>
</tr>
<tr>
<td>Secondary education and high school</td>
<td>0.8 (0.1)</td>
<td>0.2 (0.1)</td>
</tr>
<tr>
<td>Adulthood</td>
<td>0.8 (0.2)</td>
<td>0.3 (0.2)</td>
</tr>
</tbody>
</table>

Note: Language use scores represent a mean proportion (max. score = 1, min = 0) of languages’ use in different periods of life: Preschool (from 0 to 5/6 years), Primary Education (from 5/6 to 12 years), Secondary Education and High school (from 12 to 18 years) and Adulthood (from 18 to the actual age). Language proficiency scores were on a 7-point scale, in which 7 represents a very-high level and 1 a very-low level of proficiency. The self-assessed index is the average of participants’ responses for each domain (reading, writing, speaking, and comprehension). The Language proficiency Test used to assess L1 and L2 proficiency is the “Transparent Language Proficiency Test” [http://www.transparent.com/]. The total score reported in the table was obtained by averaging results in different sections of the test (grammar, vocabulary, and comprehension) across participants. In parentheses are reported standard deviations (SD).

Stimuli

Four hundred and thirty-two line-drawings of common objects, belonging to a wide range of semantic categories (e.g., animals, body parts, buildings, furniture), were selected for the study (International Picture Naming Project, see Szekely et al. 2004). Items were selected so that 53.2% were bigger than a shoebox and 42.4% were smaller than a shoebox [Note that there were other pictures, the remaining 4.4% that were not classifiable as bigger or smaller than a shoebox. These pictures were included in two subsets of pictures that were used only for the naming tasks (17% of the pictures). Note also that there were other two subsets of pictures that were used only for the semantic classification task (17% of the pictures).] Participants were told to consider the dimension of the object in the picture and then to classify the picture as bigger or smaller than a shoebox by considering whether or not the object could be inserted in a shoebox.

Pictures were assigned to 12 different subsets of 36 pictures each. The 12 subsets were matched for visual complexity [F[11, 385] = 0.740, P = 0.7, ηp² = 0.009], name agreement (reported in the IPNP database) [F[11, 385] = 0.999, P = 0.999, ηp² = 0.009], and lexical frequency in Italian and German [F[11, 385] = 0.301, P = 0.986, ηp² = 0.009]. Furthermore, half of the pictures in each set were high frequency (mean frequency = 3.3, SD = 0.3) and the other half low frequency (mean frequency = 0.9, SD = 0.2) lexical items.

Each subset was assigned to each of the experimental sessions across participants (see below).

Experimental Design

Participants were presented with 3 different blocked switching tasks, each one of them including a “Study” and 2 “Tests” blocks. During the Study blocks, participants saw pictures of common objects (pictures) and were asked either 1) to name pictures in either their L1 (German) or L2 (Italian) or 2) to classify the objects according to whether they were “bigger than a shoebox” or “smaller than a shoebox” in real life. During subsequent Test blocks, half of the pictures presented in the Study blocks were repeated along with new pictures. Thus, the picture stimuli at Test blocks had either been seen as pictures at Study (the “old” condition), or were experimentally novel (the “new” condition).

Table 2 Language switching: BSWQ and Switch questions

<table>
<thead>
<tr>
<th>Scale</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSWQ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1S</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>L2S</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>CS</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>US</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>OS</td>
<td>28</td>
<td>5</td>
</tr>
</tbody>
</table>

Switch questions

Switch in a bilingual group 4 1
Switch in a group with whom you always use your L1 2 1
Switch in a group with whom you always use your L2 3 1
Switch in a dialog (just one other person beside you) 2 1
Switch in a sentence 3 1

Note: Scores for L1S, switch to German; for L2S, switch to Italian; CS, contextual switch; US, unintended switch, and OS, overall switch.

Switch Questions scores were on a 5-point scale, in which 5 represents “many switches” and 1 “very few switches/no switches.” The self-assessed index is the average of participants’ responses for each scale.
“Study” Blocks
In each Study block, 2 sets of 36 pictures (i.e., a total of 72 pictures) were each presented 3 times, for a total of 216 trials. Participants underwent 3 Study blocks: 1) naming pictures in L1 (German), 2) naming pictures in L2 (Italian), 3) semantic classification task. In the Study block for the semantic classification task, one half of the participants started with the task asking “to classify pictures as bigger than a shoebox” and the other half with the task asking “to classify pictures as smaller than a shoebox.”

“Test” Blocks
Two Test blocks followed each one of the 3 Study blocks. In each Test block 72 pictures were presented only once, for a total of 144 trials across 2 blocks.

During each Test block, one half of the stimuli from the Study block (i.e., 36 stimuli) were intermixed with 36 novel stimuli. In one Test block, participants underwent the same task to that of the Study (i.e., naming/semantic classification task) but with the opposite decision (opposite language/opposite semantic classification decision). In the other Test block, participants underwent the different task to that of Study (i.e., if the naming task was administered at Study, the semantic classification task was performed at test and vice versa). The order of the 2 Test conditions (tasks) was counterbalanced across participants.

The stimulus manipulation was such that participants viewed both old and new pictures within each Test block (72 pictures of objects in total). Old pictures were never repeated within the Test blocks and each picture at Study was employed only once as an old stimulus in one or the other Test block (i.e., if an old picture was used in one Test block, it was not used in the other Test block).

Importantly, all Study–Tests combinations in terms of task/decision manipulation and stimulus lists (i.e., Study: 1) naming pictures in L1 (German), 2) naming pictures in L2 (Italian), 3) bigger or smaller classification; Test: 1) naming pictures in L2 (Italian), 2) naming pictures in L1 (German) 3) smaller or bigger classification) were systematically ordered, counterbalanced, and randomized between participants, to minimize any potential confounds. Participants completed 3 sets of the Study–Tests combinations.

In Figure 1, we report a schematic overview of the experimental design. For example, in set 1 a participant was first presented with naming pictures in L1 in the Study block, then to name pictures in L2 in the Test1 block, and finally to classify the pictures according to their size (i.e., bigger or smaller classification) in the Test2 block. After a 5-min pause, set 2 would start in which the Study–Test combination would change and following another 5-min pause each participant would finally undergo set 3 (see Fig. 1, for the details). Importantly, the set order (i.e., set 1, 2, and 3) was counterbalanced across participants.

Crucially, the 2 Test blocks (Test1 or Test2) implied a change in terms of “decision” or “task” as compared with the Study block. For instance, if the Study block required to name pictures in L1, Test1 would require to name pictures in L2 (i.e., opposite decision: picture naming but using a different language) and Test2 to classify pictures as bigger or smaller than a shoebox (i.e., different task: classify the object in the picture rather than naming it) or vice versa.

Experimental Procedures
Before entering the magnetic resonance imaging (MRI) scanner, participants underwent to a practice session in which they performed the 3 Study–Tests sets on a reduced number of trials (i.e., 12 trials for each Study session and 4 trials for each Test block [Also for the practice session, two sets of pictures were presented and repeated three times in the Study block. These sets contained 2 pictures each. After the Study block, in the Test1, one of the two sets (i.e., in total two repeated pictures) previously presented in the Study, was represented along with other two new pictures. After the Test1 block, the remaining set of pictures presented in the Study block was presented in the Test2 block, along with a set of new pictures. Importantly, new pictures in Test 1 and Test 2 were different]). Importantly, the pictures presented in this practice session were all different from the set of 432 pictures used in the 3 experimental sets. Stimuli characteristics, task instructions, and experimental timing were similar to those occurring during the real fMRI experiment.

Instructions were to name pictures aloud in either German or Italian (i.e., for the naming task) or classify them as bigger or smaller than a shoebox (i.e., for the semantic classification task), as fast as possible but without sacrificing accuracy. Participants were also informed that each Study or Test block would begin with a sentence indicating the task to be performed (i.e., “Nome queste immagini in italiano” or “Benenne den Namen des Bildes auf Deutsch”—name these pictures in Italian or German, respectively; “Questi oggetti sono più piccoli di una scatola da scarpe?” or “Sind diese Objekte kleiner als ein Schuhkarton?”—Are these objects smaller than a shoebox?; “Questi oggetti sono più grandi di una scatola da scarpe?” or “Sind diese Objekte größer als ein Schuhkarton?”—Are these objects bigger than a shoebox?). Importantly, we opted for vocal responses (i.e., yes or no) also for the semantic classification task, in order to control for differences in terms of articulatory processes between the naming task and semantic classification task.

Participants were also told that the tasks would appear in sets made of 3 blocks each and they would have been administered a total of 3 experimental sets. Subjects were not informed about the specific sequence of the Study–Tests combinations in each set. When the Study block in the first Study–Tests set entailed the naming task, participants always received the instructions in the language in which the first naming block was administered. If the Study block in the first Study–Tests set implied the semantic classification task, the language (i.e., German or Italian) in which instructions appeared was counterbalanced across participants. Importantly, responses for the semantic classification task had to be given in the same language indicated by the block instructions (e.g., if the instructions are given in Italian, responses should be given in that language (“Si/No” responses).

At the beginning of each block (Study, Test1, and Test2) the cue sentence indicating the task to be performed along with the block name (e.g., “Sessione A—Nome queste immagini in italiano”) was presented on a black background for 7500 ms. Following the cue sentence, each trial sequence began with a centrally placed white fixation cross (“+”) on a black background presented for 1500 ms, followed by the first picture for 1500 ms, followed by a fixation cross jittered at an interstimulus interval rate of one every 1864, 2030, 2196, or 2362 ms, in turn followed by another picture presented for 1500 msec.

Stimulus events were presented and jittered in counterbalanced orders optimized for efficient detection of contrasts between conditions of interest using a genetic algorithm (Wager and Nichols 2003), including an additional 47 “null events” (fixation crosses) for the Study blocks and 16 for each Test block presented for 1500 ms with the same jitter range to maximize statistical efficiency and facilitate deconvolution of the hemodynamic response.

Finally, at the end of each block a blank screen was presented for 2000 ms followed by an “end message” (for 10884 ms and 10 700 ms for Study and Test blocks, respectively). Stimuli were
Presented by means of Presentation software (Neurobehavioral systems: http://www.neurobs.com/).

Participants were also instructed to minimize jaw–tongue movements while producing overt vocal responses to pictures, while an experimenter outside the magnet room listened to vocal responses to each picture through an amplifier in order to classify correct responses, incorrect responses, and omissions (nonresponses) for accuracy evaluation. Due to technical constraints, vocal onset times of responses were not recorded.

**Scanning, Image Processing and Preprocessing**

The fMRI-event-related technique was used (3 T Intera Philips body scanner, Philips Medical Systems, Best, NL, 8 channels-sense head coil, sense reduction factor = 2, time echo [TE] = 30 ms, time repetition [TR] = 2000 ms, field of view [FOV] = 192 × 192, matrix size = 64 × 64, 3 mm × 3 mm in-plane resolution).

Slices were acquired axially, allowing whole-brain coverage, and were tilted parallel to the anterior commissure–posterior commissure plane (36 slices; 3-mm slice thickness). Each run was preceded by 5 dummy scans that were discarded prior to data analysis.

A high-resolution structural MRI was acquired for each participant (MPRAGE, 150 slice T₁-weighted image, TR = 8.03 ms, TE = 4.1 ms, flip angle = 8°, time between the onset of the first and last slice of one volume [TA] = 4.8 min, resolution = 1 × 1 × 1 mm) in the axial plane.

Nine fMRI sessions were acquired, equating to the 3 Study—Test sets. Five hundred thirty-two volumes were acquired during each study session, 182 were acquired during each test session.

SPM8 (Statistical Parametric Mapping) running on Matlab 7.4 (R2007a) was used for all preprocessing steps and statistical analysis.

Prior to analysis, all images for 9 sessions underwent a series of preprocessing steps. Time series diagnostics using tsdiffana (Matthew Brett, MRC CBU: http://imaging.mricbu.cam.ac.uk/imaging/DataDiagnostics) were run for the 9 fMRI sessions to check for movement artifacts in terms of abnormal variance distribution of corresponding voxels between slices and between volumes relative to mean intensity values, calculated respectively for each image or the entire time series. No high variance spikes (i.e., variance of volume changed drastically with respect to the volume immediately preceding it) due to motion or inhomogeneity of the magnetic field were evident for images in any run within each Study–Test set, except for one participant that thus was excluded from subsequent statistical analysis.

ArtRepair was used to detect bad slices in the data and to remove noise spikes due to excessive movement and other artifacts. Bad slices were then repaired by implementation of an interpolation-algorithm (from before and after scans) that employs an adaptive threshold for each slice (“Noise Filtering”), (http://cibsr.stanford.edu/tools/ArtRepair/ArtRepair.htm). Slice-timing correction was carried out by interpolating the voxel time series using sinc interpolation and resampling with the middle (15th) slice in time as a reference point.

For each Study–Test set, all slice-time corrected EPI images were realigned to the first volume in each time series and successively to...
the mean. The unified normalization–segmentation procedure was used to normalize EPI images to the MNI space with resulting voxels size of $3 \times 3 \times 3$ mm. This procedure implies 1) coregistering the anatomical $T_1$ image to the mean EPI image generated during the realignment step, 2) apply the unified segmentation to the coregistered anatomical image using the default parameters in SPM8 to estimate the normalization parameters that encode the transformation from the native to MNI space, 3) apply the normalization parameters obtained from the segmentation step to write out all normalized realigned EPI images.

The normalized EPI images were then smoothed using a 6-mm full-width at half-maximum Gaussian kernel to ensure that the data were normally distributed and to account for any between-subject residual variations prior entering statistical analysis.

**Statistical Analysis**

**Behavioral Analysis: Error Analysis**

Failures to respond to a given stimulus or erroneous responses were considered errors and were eliminated from the analyses. In the naming tasks, responses were considered correct whenever the expected name was given, but also when participants used an appropriate category label for the item (e.g., naming a “coat” as “clothes”). Similarly to previous studies (e.g., Guo et al. 2011), we used this somewhat lax criterion that we did not train participants with the experimental pictures in advance.

**fMRI data Analysis**

First-level design. The statistical analysis was performed in a 2-stage approximation to a mixed effects model. At the first level, neural activity was modeled by a delta function at picture onset. The BOLD response was modeled by a convolution of these delta functions by a canonical hemodynamic response function to form regressors in a general linear model (GLM). Each Study–Test set was analyzed in a separate GLM model. For each Study block, 6 regressors were modeled coding the first presentation, the first and the second repetition of the 2 sets of 36 pictures, which were presented each 3 times. For each Test block, 2 regressors were included in the model, one for the set of “old” pictures from the Study session (i.e., 36 stimuli) and one for the “new” pictures. To minimize the influence of signal changes due to head movement, the 6 rigid-body realignment parameters (i.e., 3 estimated translations in mms along the $x$-, $y$-, and $z$-axes and 3 estimated rotations in radians around the $x$-, $y$-, and $z$-axes for each volume) for the specific Study–Test set were included as nuisance regressors in each design matrix.

Voxel-wise parameter estimates for regressors were then obtained by restricted maximum-likelihood (ReML) estimation, using a temporal high-pass filter (cutoff at 128 sec) to remove low-frequency drifts, and modeling temporal autocorrelation across scans with an AR (1) process.

Second-level designs.

**Stimulus–response bindings in different tasks: linguistic versus nonlinguistic tasks. Images belonged to 3 repetition contrasts:**

1. L1 local control contrast: old pictures in an L1-Test block “OLD-T-L1” versus second repetition of the same pictures in the Study block “2REP-S-L2,” when the Study block involved the opposite language (i.e., L2 naming);

2. L2 local control contrast: old pictures in an L2-Test block “OLD-T-L2” versus second repetition of the same pictures in the Study block “2REP-S-L1,” when the Study block involved the opposite language (i.e., L1 naming);

3. Semantic classification local control contrast: old pictures in a Bigger/Smaller semantic classification Test block “OLD-T-B” or “OLD-T-S” versus second repetition of the same pictures in the Study block “2REP-S-S” or “2REP-S-B,” when the Study block involved the opposite decision (i.e., bigger than a shoebox or smaller than a shoebox).

The images from these 3 repetition contrasts from our whole-brain analysis were collapsed across the 3 Study–Test sets and comprised the data for the SPM8 one-way ANOVA, within subjects, which treated participants as a random effect. In addition to the 16 participants effects, this model had 3 local control condition effects, corresponding to a $1 \times 3$ (group $\times$ local control) repeated-measures ANOVA. Within this model, Statistical parametric maps (SPMs) of the $t$ statistics were created for the differences between the local control conditions when an opposite language is used for the same picture (e.g., L1 vs. L2 naming conditions) or when an opposite [semantic] classification decision is carried out (e.g., bigger vs. smaller conditions) ($P < 0.005$ uncorrected at the voxel level) and effects of interest were plotted to investigate the direction of any potential difference. Given our specific aim to test for differential local control effects in the brain areas involved in language control as identified in the neurocognitive model of bilingual language processing (i.e., Abutalebi and Green 2007, 2008) we used a more liberal threshold of $P < 0.005$, uncorrected at the voxel level, in order to trace very subtle potential changes in brain activity related to the same stimulus, which however entails the opposite language or semantic task. Post hoc directional whole-brain voxel-wise $t$-tests between conditions were then carried out in order to assess the significance of the differential effect in each area of interest.

Brain activation was localized by the Anatomy toolbox (Eickhoff et al. 2005). Significant peak activations are reported as Montreal Neurological Institute (MNI) coordinates.

**Language control: local versus global control.** A separate flexible $2 \times 2$ ANOVA factorial model in SPM8 was designed for the “global $\times$ local” control conditions (i.e., new vs. old pictures) and the “L1 $\times$ L2” naming conditions to explore specific effects related to bilingual language control. That is, effects related to the potential differences between the control mechanisms involved at the level of specific lexical items or at the level of language sets, in the same aforementioned areas included in the Abutalebi and Green model (e.g., Abutalebi and Green 2007, 2008; Green and Abutalebi 2013).

The factor matrix included contrast images relative to:

1. L1 local control contrast: old pictures in an L1-Test block “OLD-T-L1” versus second repetition of the same pictures in the Study block “2REP-S-L2,” when the Study block involved the opposite language (i.e., L2 naming);

2. L2 local control contrast: old pictures in an L2-Test block “OLD-T-L2” versus second repetition of the same pictures in the Study block “2REP-S-L1,” when the Study block involved the opposite language (i.e., L1 naming);

3. L1 global control contrast: new pictures in an L1-Test block “NEW-T-L1” versus first presentation of pictures in the Study block “1PRES-S-L2,” when the Study block involved the opposite language (i.e., L2 naming);

4. L2 global control contrast: new pictures in an L2-Test block “NEW-T-L2” versus first presentation of pictures in the Study block “1PRES-S-L1,” when the Study block involved the opposite language (i.e., L1 naming).

The factor “subject” was additionally included in the factor matrix to control for the repeated measures.

In this model, a single $F$-test was performed testing for significant differences among the 4 Control $\times$ Language conditions.
Effects of interest were plotted to investigate the direction of any potential difference between L1 and L2 at the language set level (i.e., global control) or 2) at the specific lexical level (i.e., local control). Furthermore, we also explored possible interaction effects between control (i.e., local and global) and language (i.e., L1 and L2) conditions. Post hoc directional whole-brain voxel-wise T-tests between conditions were then carried out in order to assess the significance of any differential effect in each area of interest. Brain activation was localized by the Anatomy toolbox (Eickhoff et al. 2005). Significant peak activations are reported as MNI coordinates.

Results
Stimulus–Response Bindings in Different Tasks: Linguistic versus Nonlinguistic Tasks
The F-contrast testing for S–R binding differences between the local control conditions, when an opposite language is used for the same picture (i.e., L1 vs. L2 naming condition) or when an opposite (semantic) classification decision is carried out (e.g., bigger vs. smaller conditions), was computed in the areas included in the bilingual language production model (Abutalebi and Green 2007; Green and Abutalebi 2013). These areas included the LPFC, the dACC/pre-SMA, LIPL, RIPL, and RPFC. The critical threshold (i.e., considered at P < 0.005 uncorrected at the voxel level) was set at P < 0.0027 corrected for a total of 18 local control condition × Area of Interest post hoc tests (i.e., 0.05/18—maximum number of post hoc comparisons). Effects of interest were plotted to investigate the direction of any potential difference between local control conditions.

The one-way ANOVA revealed significant differences in the LPFC ($x = -45, y = 47, z = 10; k = 35$), the LIPL ($x = -51, y = -46, z = 46, k = 39$), the RIPL ($x = 60, y = -52, z = 34, k = 10$), the dACC/pre-SMA ($x = 12, y = 11, z = 49; k = 13$) and 2 clusters in the RPFC ($x = 39, y = 32, z = -5, k = 11; x = 39, y = 35, z = 10, k = 6$).

Post hoc directional T-tests revealed that 1) the differences observed in LPFC, LIPL, RIPL, and the RPFC cluster located in the right inferior frontal gyrus (RIFG, pars triangularis) ($x = 39, y = 35, z = 10$) were related to significant BOLD increases for L1 local control contrast conditions with respect to a significant decrease in L2 local control contrast conditions; 2) the effects highlighted in the RIFG (pars orbitalis) ($x = 39, y = 32, z = -5$) were driven by an incremental difference from a significant BOLD decrease in the L2 local control contrast conditions, to a negligible effect in L1 local control contrast conditions to a significant increase in the local control conditions for the semantic classification task; 3) a significant difference emerged in the dACC/Pre-SMA ($x = 12, y = 11, z = 49; k = 13$), due to a significant increase in BOLD signal for the L2 local control contrast conditions with respect to the other 2 local control conditions (see Fig. 2).

In order to test the hypothesis that activation in areas sensitive to S–R binding strength for the 2 language conditions (i.e., L1 and L2) will overlap with activation elicited by a condition

![Figure 2. Stimulus–Response bindings in different tasks: Linguistic versus Nonlinguistic tasks. Columns 1–3 refer to the local control conditions for L1 naming, L2 naming, and semantic classification task, namely to the parameter estimates for: 1) L1—Local control, 2) L2—Local Control, and 3) semantic classification —Local control. The F-contrast showing differences between the 3 conditions in areas of interest is superimposed on the default SPM gray matter tissue prior map in MNI space.](http://cercor.oxfordjournals.org/)

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entailing no language decision (i.e., semantic classification task), we conducted a conjunction analysis for conjoint activation between the 3 local control conditions (i.e., L1 local control, L2 local control, and Semantic classification local control) assessed at a threshold of $P < 0.005$ (uncorrected). The conjunction analysis revealed that exclusively LPFC ($x = -48$, $y = 32$, $z = 22$) was commonly engaged by local control in both opposite language and semantic conditions (see Fig. 3).

**Language Control: Local versus Global Control**

The $F$-contrast testing for significant differences among the 4 Control $\times$ Language conditions (at $P < 0.005$ uncorrected at the voxel level) revealed significant differences in the areas included in the language control network (Abutalebi and Green 2007, 2008; Green and Abutalebi 2013). Namely, in the LPFC ($x = -42$, $y = 47$, $z = 10$, $k = 123$), LIPL ($x = -48$, $y = -52$, $z = 49$, $k = 84$), RIPL ($x = 60$, $y = -55$, $z = 31$, $k = 69$), and RPFC ($x = 39$, $y = 38$, $z = 10$, $k = 34$). The critical threshold (i.e., considered at $P < 0.005$ uncorrected at the voxel level) was set at $P < 0.002$ corrected for a total of 24 “Control $\times$ Language” condition $\times$ Area of Interest post hoc tests (i.e., 0.05/24—maximum number of post hoc comparisons).

Plots of parameter estimates for each condition in each area of interest revealed that differences in LPFC, LIPL, RPFC, and RIPL were related to a main effect of language, in terms of an increase of BOLD signal for both the L1 local and global control conditions and a significant decrease for the respective L2 conditions.

Additionally, post hoc directional $T$-tests revealed that 1) a difference in BOLD signal elicited in the head of the LC ($x = -15$, $y = 23$, $z = 4$, $k = 13$) emerged between L1 and L2 conditions (i.e., higher for L1); 2) a large cluster peaking in the dACC ($x = 0$, $y = 23$, $z = 49$, $k = 193$) and extending to pre-SMA was highlighted for the difference between local and global control conditions exclusively for L2 (see Fig. 4).

![Figure 3. Stimulus–Response bindings in different tasks: Conjunction analysis. Conjoint activity in LPFC for the 3 local control conditions relative to L1 naming, L2 naming, and semantic classification task with the relative parameter estimates.](http://cercor.oxfordjournals.org/)

![Figure 4. Language Control: Local versus Global Control. Columns 1–4 refer to the local and global language control conditions and namely to the parameter estimates for: 1) L1—Local control, 2) L2—Local Control, 3) L1—Global Control, and 4) L2—Global Control. The F-contrast showing differences between the 4 conditions in areas of interest is superimposed on the default SPM gray matter tissue prior map in MNI space.](http://cercor.oxfordjournals.org/)
Discussion

In this fMRI study, we employed linguistic and nonlinguistic blocked switching tasks in order to widen our knowledge of the neural basis of language control in bilinguals. We focused on brain areas known to be involved in bilingual language control as outlined in a neurocognitive model (Abutalebi and Green 2007, 2008; Green and Abutalebi 2013). This model identifies a network of specific brain areas subsuming cognitive control processes, which are involved in language control in bilinguals at different stages and at different levels of processing.

In the present study, participants were asked to perform a linguistic task (naming in 2 languages, L1 and L2, respectively) and a nonlinguistic task (semantic classification with 2 criteria such as classifying pictures as bigger or smaller than a shoebox). Two main issues were explored.

First, we assessed the effects of establishing new S–R bindings as a consequence of changing the task, for the 2 different tasks (linguistic and nonlinguistic tasks). This exploration would help to understand the extent to which the bilingual language control network is modulated when controlling nonlinguistic representations. This issue has not been studied so far and the main aim of the present study was to unravel the neural underpinnings of these effects.

Second, we assessed the effects of switching languages for items that were repeated across the languages and for items that were not repeated. The first effect would inform us about the so-called local control and the second one about the so-called global control.

Stimulus–Response Bindings in Different Tasks: Linguistic versus Nonlinguistic Tasks

The first question of the present study (i.e., whether the type of S–R bindings modulates the activity in the language control network) was addressed by comparing brain activity elicited by changing the S–R bindings for repeated stimuli across different tasks (L1 naming, L2 naming, and semantic classification task). A crucial finding was that 2 brain areas, that is, the LPFC and the LIPL, were similarly involved in the engagement of S–R bindings for L1 naming and in those for the semantic classification task. This may indicate that there are some common mechanisms between the control of the linguistic and the nonlinguistic representations [We acknowledge that the semantic classification task might involve some word access. This represents a potential shortcoming when interpreting commonalities between the effects found for L1 naming and for the semantic classification task. However, recent research suggests that the linguistic processes involved in naming tasks seem to be different from those involved in semantic classification tasks. In fact, the work of Strijkers et al. (2011) reveals that when there is actually the intention to name an object, there seems to be a top-down modulation of the processes in charge of lexical access that speeds up word retrieval. As shown by these authors, this top-down modulation is not present in the semantic classification task. Moreover, if the similarity between the network activated during L1 naming and the semantic classification task is due to the fact the semantic decision is driven by linguistic encoding, hence, we should have observed also a consistent overlap between the semantic task and L2 naming. Note that the yes/no response were given also in L2 and therefore the classification decision should have been guided also by encoding in L2. Since we did not observe such overlap, it is difficult to conclude that similarities between L1 naming and semantic classification task is due to linguistic encoding in L1.]

Given these considerations, and although we cannot definitely argue that there is no word activation in the semantic classification task, we believe that the differences between the naming task and semantic classification task are meaningful enough to grant a comparison.). Both are characterized by a decision that implies general attention processes not specifically bound to the nature of the elements considered for the decision. However, the nature of the stimulus and response will drive more or less activity in other areas on the basis of the specific nature of the stimuli, the strength of task sets and according to specific task goals, which convey the response. For both tasks, increased LPFC activity may reflect the neural tuning for reestablishing new S–R bindings as a function of efficacious selection of the target, in contexts in which interference from the previous task is still present (Szameitat et al. 2002; Collette et al. 2005). Instead, increased LIPL activity may reflect processes to configure and adjust the current task-set parameters, by biasing selection away from the task-set recently abandoned and in turn, by signaling to the LPFC attention shifts induced by stimuli information (Sigman and Dehaene 2006; Rowe et al. 2008).

However, we also observed some differences between the linguistic and the semantic classification task regarding local control. That is, on one hand, an increased “priming disruption effect” was evident in the RIFG (pars orbitalis) (see Fig. 2), which appeared to significantly respond (increased BOLD signal) in the semantic classification task with respect to the 2 linguistic tasks (i.e., naming in L1 and naming in L2). Interestingly, the RIFG has been previously related to domain-general inhibitory control (Jahfari et al. 2011; Forstmann et al. 2008; Aron et al. 2004, 2014). Hence, the fact that we found activity in this region (with stereotactical coordinates similar to the ones reported by the above-mentioned studies) as being significantly disrupted in the semantic classification task as compared with the 2 linguistic tasks, might suggest that semantic classification task entails a greater cognitive effort to detect salient cues in a task where individuals are asked to classify items on the basis of perceptual saliencies. On the other hand, we observed decreased activity within the dACC/pre-SMA complex for the semantic classification task, possibly indicating that binding of nonlinguistic S–R representations (at least for the task here employed) is in lesser need of monitoring resources than linguistic ones such as L2 naming.

Taken together, our results for the S–R bindings in different tasks show that there are important commonalities between linguistic and nonlinguistic local control, chief among them the BOLD responses in the LPFC and LIPL. However, we also report some crucial qualitative differences such as in the RIFG (pars orbitalis) and in the dACC/pre-SMA complex.

As to the differences between the 2 linguistic tasks, we report that brain areas involved in engaging S–R bindings in the L1 naming context (naming L1 after having named L2) were associated to significantly increased priming disruption effects in the LPFC, the LIPL, the RIPL, and in a RFFC cluster located in the RIFG (pars triangularis). Importantly, these areas showed an opposite pattern of activity (i.e., significant deactivation) in the L2 context (naming L2 after having named L1). This may suggest that establishing new L2 S–R bindings after switching required less control than establishing L1 S–R bindings after switching.

At a first view, this may seem a paradox and contrary to our own and other various neuroimaging findings in studies that employed trial-by-trial language-switching tasks (e.g., Wang et al. 2007; Abutalebi, Della Rosa, Castro Gonzalez, et al. 2013; Abutalebi, Della Rosa, Ding; et al. 2013). In those studies, usually switching into L2 (or in the less dominant language) was paralleled by
increased activity in language control areas, considered as inhibition-related activity necessary to overcome the prepotent language (L1) used in the preceding trial. The paradigm used in the present study does not allow us to infer over such fast control processes (i.e., transient control). Rather, the present study was designed to investigate “priming disruption effects” and different response selection bindings in bilinguals. Interestingly, with the possible exception of the dACC/pre-SMA, we report a reverse pattern of brain activations as that usually found in trial-by-trial language-switching neuroimaging studies. Indeed, local control in L1 (i.e., naming in L1 after the same pictures were presented several times in L2 in a timely distinct previous run) was associated to more extensive engagement of language control areas. However, these findings are in line with behavioral studies of language switching reporting an asymmetric RT cost with naming in a more proficient (dominant) L1 slower after naming in the less proficient L2 (Meuter and Allport 1999; Costa and Santesteban 2004). Further, the neural pattern of results is also consistent with previous ERP studies (e.g., Branzi et al. 2014). Within language repetition trials usually lead to repetition priming, that is, to faster reaction times for the second repetition of the very same item. However, such priming is affected in an illustrative way when changing the language. That is, priming effects are absent when naming in L1 after having named the pictures in L2 (as compared with L1 naming without previous use of L2); but they are present in the opposite direction (i.e., when naming in L2 after having named the pictures in L1 as compared with L2 naming without previous use of L1).

We have also observed an interesting asymmetry regarding the pattern of brain activity according to the direction of the language switch. In detail, we revealed naming a set of pictures in L1 after having named them in L2 might lead to an increased engagement of brain regions involved in language control as compared with the opposite direction. Presumably, this is because of the necessity to override the inhibition of the prepotent L1 during the previous L2 block. Instead, since this extra-activity is not necessary while naming first in L1, during subsequent L2 naming reduced language control related activity might be observed with the exception of the dACC. Importantly, the dACC activity might specifically indicate that L2 production prominently drives monitoring and error detection processes. Indeed, the dACC/pre-SMA activity has been related to conflict monitoring (Botvinick et al. 1999). Recently, it has been shown that the dACC/pre-SMA plays a major role in tasks involving conflict resolution subserving selection of the targeted response in both linguistic and nonlinguistic contexts (Abutalebi et al. 2012). Related to our study, we suggest that in the L2 naming context, the priming disruption effect is grounded within the necessity to actively monitor S–R binding configuration in L2 to allow successful production. This activity in the dACC/pre-SMA may reflect monitoring while updating response selection processes when establishing new S–R bindings in L2 (after L1 production), in order to hinder the production of unwanted, but still prepotent targets in L1 (Collette and Van der Linden 2002).

Our findings may have important implications for neurocognitive models of bilingual language control, allowing us to postulate a possible functional dissociation between the brain areas responsible for cognitive control. The LPFC, RFPC, LIPL, and RIPL were all found to be more engaged for local control in L1, while the dACC/pre-SMA complex was more active for local control in L2. We suggest that language control in bilinguals is hierarchically organized. On one hand, the language control mechanism lays upon a supervisory attentional system neurally identified in the dACC/pre-SMA complex. On the other hand, language control is also supported by a response selection system, comprising inferior parietal and prefrontal areas. The engagement of the latter is tailored to convey attentional resources for response selection purposes and is regulated by the amount of inhibition necessary to overcome L1 coactivation during L2 naming. The dACC/pre-SMA is recruited instead for increased attentional and monitoring demands as in the case of L2 naming after L1 naming, notwithstanding any facilitatory priming effects driven by L1.

The findings for local control in L1 and L2 reported in our study are in accord to what Guo et al. (2011) highlighted for their global control conditions. Indeed, Guo et al. (2013) found that naming in L1 after L2 (on the same stimuli) as compared with L1 in a first block elicited the activation of a network of frontal and parietal brain areas. Instead, naming in L2 after L1 (on the same stimuli) as compared with L2 in a first block activated posterior brain areas, such as the cuneus and the precuneus, notoriously not involved in language and cognitive control. However, as aforementioned Guo et al. (2011) improperly refer to this condition as a global control condition, since by definition the control on a subset of lexical items that were previously presented in the other language is usually referred to as local control. De Groot and Christoffels (2006) provided a clear distinction between global control, where control involves the activation and/or inhibition of complete language systems, and local control, where control is exerted a restricted set of lexical representations (i.e., those previously used in a different language). Taken together, the asymmetries observed in our study may be explained by assuming that disengaging from L2 lexicon to access the L1 lexicon is more demanding than the reverse, as indicated by the engagement of the response selection areas of the language control network. In other words, at least in bilinguals with 2 languages not equally balanced in terms of dominance and use (Recall that the bilinguals that participated to this study had similar proficiency in both the languages but they were not balanced in the use of the two languages (see Table 1)), the language control brain network is involved to a different extent depending on whether the language to be produced is L1 or rather L2.

The Prefrontal Cortex and Response Selection

One of our main aims was to better characterize linguistic and nonlinguistic local control functions and identify areas of conjoint activity for engagement of S–R bindings across linguistic and nonlinguistic tasks. For this purpose, a conjunction analysis between the 3 local control conditions was carried out (i.e., L1 local control, L2 local control, local control of the semantic classification task). Strikingly, we found that the LPFC was conjointly recruited, across all the local control conditions (see Fig. 3).

This result underlines that the LPFC has a general key role in the implementation of S–R bindings during response selection (e.g., Miller and Cohen 2001; Ridderinkhof, Ullsperger, et al. 2004; Ridderinkhof, van den Wildenberg; et al. 2004), notwithstanding the nature of the representations involved. In more general terms, it has been suggested that the lateral PFC is tuned for adaptation of response sets as a function of efficient selection of the target stimulus in contexts with interfering information (Szameitat et al. 2002; Ridderinkhof, Ullsperger, et al. 2004; Ridderinkhof, van den Wildenberg; et al. 2004; Collette et al. 2005). Furthermore, on the basis of the present findings we suggest that the extent to which this area is involved in response selection seems to be bound to the strength of the previous S–R bindings (formed during the Study block), which should then be overcome during the subsequent task in the Test block. This conclusion is supported by the observation that in order to
overcome L2-S-R bindings to set new L1-S-R bindings, increased LPFC activity is required than in the opposite situation (i.e., when naming first in L1 and then in L2). Assuming that the strength of the binding is inversely related to the strength of the language (i.e., overcoming L2-S-R bindings is harder than overcoming L1-S-R bindings), it is reasonable to conclude that the involvement of the LPFC is related to the degree of cognitive effort imposed by control demands for the engagement/disengagement of response sets with different S-R strengths. Regarding the control of semantic S-R bindings we found them to recruit the LPFC to the same extent as for the control of L1-S-R bindings. As explained above, this result suggests that the LPFC has a domain-general role for the selection of target responses in contexts in which high interference is present.

Language Control: Local versus Global Control

The second question of this study concerned the representation of the same task-control brain areas, although the processing of the languages for activity in the brain areas of the neurocognitive system (i.e., LPFC, LIPL, RPFC, and RIPL) of the language control network. Indeed, only L1 local and global control were paralleled by increasing activity of the LPFC, LIPL, RPFC, and RIPL (and the head of the LC, see below for discussion) which assumes that, naming in L1 (independently of encountering a new or an old stimulus) after naming in L2 is enacted by the activity in these areas with the L1-L2 block.

Additionally, our post hoc directional T-Tests revealed a difference in BOLD signal elicited in the head of the LC between L1 and L2 conditions being higher for L1, while a large cluster in the dACC/pre-SMA complex for the difference between local and global control conditions appeared exclusively for L2. Again as aforementioned, these effects confirm a sort of dissociation between languages for activity in the brain areas of the neurocognitive model proposed by Abutalebi and Green (2007, 2008). At a first view, these findings seem to be in contradiction with the findings of Guo et al. (2011) who report a neural dissociation between local and global control. Indeed, the authors report the dACC/pre-SMA involved in local inhibition, while the left frontal gyrus and parietal cortex played an important role for global inhibition. The authors compared language control in a trial-by-trial switching paradigm to language control in a similar paradigm as the one used here for local control (i.e., naming the same picture seen before in a different language block). Both these processes may be referred to as local control, since only repeated pictures were used throughout the tasks with the switching paradigm relying on fast transient trial-by-trial control processes and the blocked naming paradigm relying more on sustained control processes. The notion of global control refers to when a bilingual encounters a word or a stimulus not previously seen, and presumably this would activate the whole language system (as opposed to the activation of a subset of lexical items when previously encountering its translation equivalents). This was not specifically addressed in the study of Guo et al. (2011). Interestingly, we here report that both local and global processes are carried out in a similar fashion, but with an effect of language dominance. Indeed, we have shown a specific L1 increased effect for both types of control mirrored by a significant L2 activity decrease. This effect was also present in the head of the LC. The LC has been specifically linked to language control in bilinguals (Crinion et al. 2006; Abutalebi, Della Rosa, Castro Gonzalez et al. 2013; Abutalebi, Della Rosa, Ding et al. 2013) and in the neurocognitive model of Abutalebi and Green (2007, 2008) it is thought to be a relay station in the network, since it conveys communication between the dACC/pre-SMA and the prefrontal cortices for control and selection (Abutalebi and Green 2008). Moreover, the fact that the LC activity affects similarly local and global control indicates that its control mechanisms are applied on the whole language set. This evidence is in line with previous studies highlighting the key role of subcortical structures in bilingual language control. These areas are generally modulated by language dominance. Apart from the LC, also the putamen was reported to be involved during language production and some studies have related left putaminal activity particularly to the control required for articulatory processes (see Abutalebi, Della Rosa, Castro Gonzalez et al. 2013; Abutalebi, Della Rosa, Ding et al. 2013). More recently, Hervais-Adelman et al. (2014) proposed that the left putamen might have a specific role in language control especially in high demanding control conditions, such as in the case of simultaneous interpreting (SI). The authors revealed the putamen was modulated according to the duration of the overlap between listening and speaking during SI, likely reflecting the extra-effort required to suppress the output level the words of the inappropriate language while simultaneously hearing speech in that language. Note that in the present study we did not focus on the involvement of this area since our task did not involve the same degree of control as during SI.
Conclusion

Our present data allow us to functionally differentiate the language control network in bilinguals. On the one hand, we identify a cortical network of bilateral frontal and parietal areas such as the PFC and IPL, with the possible support of the head of the LC, defining the response selection system of language control, responsible for both engagement and disengagement of inhibitory control during language production. Interestingly, some of the brain areas of this response selection system, particularly the LPFC, seem to be similarly involved in the control of the semantic classification involved. This network acts on both local and global control, when facing increased attentional and monitoring needs such as when naming in the weaker language.

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Notes

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