NeuroImage 90 (2014) 348–359

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Domain-general inhibition areas of the brain are involved in language switching: FMRI evidence from trilingual speakers

Angela de Bruin [a,*], Ardi Roelofs [a], Ton Dijkstra [a], Ian FitzPatrick [a,b]

[a] Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, P.O. Box 9104, 6500 HE Nijmegen, The Netherlands
[b] Heinrich Heine Universität Düsseldorf, Institut für Sprache und Information, Universitätsstraße 1, 40225 Düsseldorf, Germany

ARTICLE INFO

Article history:
Accepted 23 December 2013
Available online 30 December 2013

Keywords:
Inhibition
Executive control
Language switching
Trilingual
FMRI

ABSTRACT

The prevailing theory of language switching states that unbalanced bilingual speakers use inhibition to switch between their languages (Inhibitory Control or IC model; Green, 1998). Using fMRI, we examined the brain mechanisms underlying language switching and investigated the role of domain-general inhibition areas such as the right inferior frontal gyrus (rIFG) and the pre-supplementary motor area (pre-SMA). Dutch–English–German trilinguals performed a picture naming task in the MRI scanner in both a blocked-language and a mixed-language context. The rIFG and pre-SMA showed more activation for switches to the second and third language (L2 and L3) compared to non-switch trials and blocked trials. No such difference was found for switches to the first language (L1). Our results indicate that language switching recruits brain areas related to domain-general inhibition. In this way, our study supports the claim that multilinguals use inhibition to switch between their languages.

Introduction

Bilinguals are able to switch, seemingly effortlessly, between the languages that they speak. An important question is how they manage to do this. Green's Inhibitory Control (IC) model (1998) proposed that language switching is controlled by language-external inhibitory control networks. When a bilingual names an object, multiple lexical items in both languages become active and compete for selection (e.g., Hermans et al., 1998). Only the item with the highest level of activation, however, will ultimately be selected. This can be achieved by inhibiting the lexical items in the non-target language. A first assumption of the IC model is that the amount of inhibition depends on the speaker's relative proficiency in a language. In unbalanced bilinguals, the first language (L1) is usually more dominant than the second language (L2). The IC model predicts more inhibition of the stronger L1 when speaking in L2, compared to less inhibition of the weaker L2 when speaking in L1. A second assumption holds that it takes time to overcome this inhibition. On the one hand, naming in L2 requires more inhibition of the stronger L1. As a consequence, it takes more time to switch back to L1, prolonging response time (RT). On the other hand, naming in L1 requires less inhibition of the weaker L2 and therefore it takes less time to switch to L2.

Abutalebi and Green (2008) proposed a related model that accounts for language switches by specifying the brain networks involved in language switching. According to this model, language switching is instantiated by brain regions also related to executive control, such as the anterior cingulate cortex (ACC) and caudate nucleus. These brain regions are involved in various aspects of executive control, such as conflict resolving, but they aren't involved in inhibition in particular (Barbey et al., 2012; Collette et al., 2005; Niendam et al., 2012). Two brain regions that are specifically associated with inhibition, the right inferior frontal gyrus (rIFG) and pre-supplementary motor area (pre-SMA) (Jahfari et al., 2011), are not included in this model and also often missing in fMRI studies on language switching. In our study, we specifically wanted to address the role of these inhibition-related brain regions in language switching. In this way, we wanted to test the role of inhibition as predicted by Green's IC model (1998). We first discuss relevant behavioural and EEG studies on language switching that have considered the involvement of inhibition in language switching. Whereas some of these studies claim to have found evidence supporting the role of inhibition in language switching, others have challenged the necessity of inhibition.

Behavioural and EEG studies on language switching

Language switching studies have often used picture or digit naming experiments, in which participants name two consecutive trials in the same language (non-switch trials) or in different languages (switch trials). The difference in naming latencies between switch and non-switch trials is defined as the switch cost. Meuter and Allport (1999) were among the first researchers to conduct a switching study in bilingual language production. In their experiment, unbalanced bilinguals were asked to name digits according to a colour cue in either their L1 or their L2. Naming latencies were longer in switch trials than in non-switch trials, but this effect was asymmetrical for the two languages: Switching to L1 required more time than switching to L2. This larger

* Corresponding author at: Human Cognitive Neuroscience, University of Edinburgh, 7 George Square, Edinburgh EH8 9JZ, UK.
E-mail address: angela.debruin@ed.ac.uk (A. de Bruin).

1053-8119/$ – see front matter.
http://dx.doi.org/10.1016/j.neuroimage.2013.12.049

L1 switch cost is often taken as evidence supporting the IC model, because more time is needed to overcome L1 inhibition. Further evidence for the role of inhibition in language switching was collected in EEG experiments focussing on the N2 component of the event-related brain potential (ERP), which is said to reflect inhibition. Jackson et al. (2001) found an asymmetrical behavioural effect: Switching to L1 was slower than switching to L2. The ERP data showed an increased N2 ERP component for switch compared to non-switch trials. Interestingly, this N2 effect was only significant for switches to L2 (requires more inhibition of L1), but not when switching to L1 (requires less inhibition of L2). These findings are in line with the IC model.

Although most language switching studies have involved bilingual speakers, some studies have also tested multilinguals with three or four languages (e.g., Costa et al., 2006; Philipp et al., 2007). Multilingual speakers can inform us about the role of language strength in language switching, as the same speaker has to control multiple non-native languages that differ in strength. L1 switch costs in RTs were found to be larger than L2 or L3 switch costs. Furthermore, L2 switch costs were larger than L3 costs (Schwieter, 2013; Schwieter and Sunderman, 2011).

There are, however, also studies that argue against the necessity of inhibition in (certain instances of) language switching. For instance, Costa and Santesteban (2004) replicated the finding of asymmetrical switch costs in unbalanced Catalan–Spanish bilinguals. In balanced trilinguals with equal proficiency in Spanish and Catalan, however, switch costs were not only symmetrical for L1 and L2, but also for a weaker L3. Costa and Santesteban concluded that unbalanced bilinguals might rely on inhibition, whereas balanced bilinguals might use other mechanisms to select the target language. Other studies have challenged the necessity of inhibition even in unbalanced bilinguals. When unbalanced bilinguals could voluntarily switch between languages, switch costs to L1 and L2 were symmetrical (Gollan and Ferreira, 2009). Verhoef et al. (2009) found both symmetrical and asymmetrical switch costs within one group of unbalanced bilinguals, depending on the preparation time for a picture stimulus. Whereas a short time-interval between language cue and picture resulted in asymmetrical switch costs, a longer interval yielded symmetrical costs and a larger N2 amplitude. Christoffels et al. (2007) also conducted an EEG experiment on bilingual picture naming in blocked- and mixed-language contexts. In the blocked context, when all pictures were named in either German or Dutch, L1 naming was faster than L2 naming. In contrast, when participants had to switch between L1 and L2 in the mixed context, L2 naming was slightly faster than L1 naming. Switch costs, however, were symmetrical for L1 and L2. The ERP data showed an increased amplitude for non-switch compared to switch trials for L1 naming, but no such difference for L2 naming. Taken together, these results are difficult to reconcile with the IC model and suggest that language switching, even in unbalanced bilinguals, might be instantiated by mechanisms other than inhibition.

In summary, some but not all studies have found asymmetrical switch costs in RTs and clear evidence supporting inhibition. Some behavioural studies have obtained asymmetrical switch costs that support the IC model. However, other studies have challenged the involvement of inhibitory mechanisms underlying language switching. It is therefore questionable whether an (a)symmetry in switch costs alone could inform us whether inhibition is involved in language switching (cf., Runnqvist et al., 2012). In all, behavioural and EEG studies alone do not seem to provide unequivocal evidence in favour of the IC model. Next, we consider whether fMRI studies shed more light on the brain mechanisms involved in language switching. We first discuss the literature on brain areas involved in inhibition in general and then provide an overview of fMRI studies on language switching in particular.

FMRI studies on inhibition and language switching

Several studies (cf., Aron, 2007; Aron et al., 2004a,b; Forstmann et al., 2008; Jahfari et al., 2011; Van den Wildenberg et al., 2010) have found that the rIFG, pre-SMA, and subthalamic nucleus (STN) are important brain areas for domain-general inhibition. Aron et al. (2004a) compared patients with a lesion in either the right or the left IFG in a stop-signal task requiring response inhibition. Patients with a rIFG (but not lIFG) lesion showed disrupted inhibition of inappropriate responses. Furthermore, the damage to the rIFG correlated with the time needed to inhibit these responses. Jahfari et al. (2011) looked at effective connectivity patterns during a combined Simon and stop-signal task. Participants had to respond to a coloured shape by pressing either a left or a right button. The response button could match or mismatch the spatial location of the stimulus. On one-third of the trials, participants heard a stop signal after the stimulus presentation, indicating that they had to inhibit their response. Brain activity during stop signals was explained best by a right-lateralized network including a fast and direct pathway between the rIFG, pre-SMA, and STN, showing that these areas are involved in inhibition. The rIFG and pre-SMA are also active during speech inhibition (Xue et al., 2008). Both the inhibition of manual responses as well as of speech production (letter and pseudoword naming) elicited activation in the rIFG and pre-SMA. Focussing on the STN, there was significant activation in manual inhibition, but not during speech inhibition. The common activation of the rIFG and pre-SMA in inhibiting both speech and manual responses suggests that these areas are part of a domain-general response inhibition mechanism.

Surprisingly, although inhibition might play an important role in language switching, fMRI studies on language switching have not directly investigated brain regions related to domain-general inhibition. Rather, they often report activation in areas related to other aspects of executive control. In their review of language switching studies, Abutalebi and Green (2008) proposed a brain network for language switching that is also important for executive control outside language. According to their model, language switching requires activation of a network including the prefrontal cortex, ACC, caudate nucleus, and supramarginal gyrus. The recruitment of these areas is not specific to language switching. The ACC is involved in error detection, conflict monitoring, and conflict resolution (Aarts et al., 2008; Kerns et al., 2004). Similarly, activation in the basal ganglia does not seem to be language specific, as they are activated in motor control and planning in general as well as in executive control (Cools, 2011; Frank, 2011; Graybiel, 2000). Because these areas also play a role in executive control outside language, it is suggested that language switching does not require a 'special' language system, but rather engages domain-general executive control functions (Abutalebi and Green, 2008). In a meta-analysis of fMRI studies on language switching, Luk et al. (2012) also reported eight areas related to executive control or language processing: Left inferior frontal gyrus (IFG), left middle temporal gyrus (MTG), left middle frontal gyrus (MFG), right precentral gyrus, right superior temporal gyrus (STG), pre-SMA, and bilateral caudate nuclei. This analysis is largely compatible with the model proposed by Abutalebi and Green (2008), although the ACC is missing in this study. Nevertheless, whereas both Abutalebi and Green (2008) and Luk et al. (2012) discuss several areas related to executive control, the rIFG and pre-SMA (important nodes in the inhibition network), are missing or only briefly mentioned.

Several fMRI studies on language switching have found activation in the brain regions discussed by Abutalebi and Green (2008) that are related to language or executive control. The dorsolateral prefrontal cortex (DLPFC) showed increased activation when early Spanish–English bilinguals named pictures in a mixed compared to blocked manner (Hernandez et al., 2000). Other studies have shown that these brain regions related to executive control are especially needed when switching to the L2. Wang et al. (2007) reported that L2 switching compared to non-switching activated the ACC, left frontal gyrus, SMA, and left temporal gyrus. Similarly, Hosoda et al. (2012) reported that switching to L2 compared to switching to L1 yielded greater activation in the right DLPFC, left superior temporal gyrus, ACC, left IFG, and left caudate nucleus. Abutalebi et al. (2013a) also found activation in the left caudate

nucleus and a cluster of the pre-SMA/ACC in trilingual language switching compared to non-switching. Only activation in the caudate nucleus, however, was influenced by language proficiency.

Although most language switching studies have focussed on local switch costs in a mixed context only, Guo et al. (2011) compared the brain mechanisms of local versus global inhibition. Local inhibition was defined as the control over a restricted set of memory items (e.g., specific lexical items) and was tested by comparing mixed- to blocked-language naming. In contrast, global inhibition was described as the activation or inhibition of the entire language system. This was examined by comparing the order of languages within the blocked naming context: L1 naming after L2 naming, versus L1 naming before L2 naming. Different brain regions were said to be active during global and local inhibition. During global inhibition, activation in the DLPFC and the parietal cortex was found. Local inhibition was reflected in increased activation in the ACC and SMA. This study, however, labelled these brain mechanisms a priori as 'inhibitory'. It is questionable whether the ACC and SMA can truly be argued to reflect inhibition, as they are not linked to inhibition in particular, but rather to other aspects of executive control. Taken together, these studies showed that language switching activated executive control areas, while no evidence for inhibition-specific activation was obtained.

Summarizing, multiple brain regions have been found to play a role in language switching: Left IFG, MTG, STG, precentral gyrus, DLPFC, ACC, SMA, and striatum. These brain areas are involved in language processing or belong to the frontoparietal network that has been linked to various aspects of executive control (e.g., Niendam et al., 2012). None of the available fMRI studies, however, have directly focussed on the role of domain-general inhibition networks in language switching. Two brain regions that have been linked to inhibition in particular, the rIFG and pre-SMA (Jahfari et al., 2011), are missing in most fMRI studies on language switching. Rather, the claim of inhibition is often based on activation in brain areas such as the ACC that are related to, amongst others, conflict resolution instead of inhibition.

Current study

The current study therefore aimed to examine the role of domain-general inhibition areas in language switching. We used fMRI to investigate the brain mechanisms involved in language switching and we specifically wanted to compare the role of inhibition networks in switching to non-native languages (L2, L3) versus switching to the native language (L1). To investigate this question, participants performed an overt picture naming experiment in the MRI scanner. Pictures were named in a blocked context (all pictures named per language) and in a mixed context (pictures named interchangeably in all three languages). The mixed context consisted of both switch trials and non-switch trials. We focussed on local inhibition only and tested the presence of such inhibition in two ways: As the difference between switch and non-switch trials, and as the difference between mixed and blocked naming. Following the IC model (Green, 1998), we predicted to find (local) inhibition during language switching, reflected by more activation in the rIFG and pre-SMA (Jahfari et al., 2011). We expected more inhibition-related activity during switch than non-switch trials, specifically for L2 and L3, because switching to these weaker languages requires inhibition of L1 (Green, 1998). Comparing blocked naming to mixed naming, we predicted to find more inhibition-related activity in the mixed context. Again, we specifically expected this difference between blocked and mixed naming to be larger for L2 and L3 than for L1. Besides the rIFG and pre-SMA (specifically related to inhibition), we expected to find activation in previously reported areas such as the ACC and DLPFC (related to other, non-inhibitory, aspects of executive control).

Besides this main issue, we also wanted to examine the link between language switching and performance on non-linguistic inhibition tasks. Many researchers have claimed that language switching is related to non-linguistic inhibition tasks and task switching (e.g., Bialystok et al., 2004; Weissberger et al., 2012). Linck et al. (2012) also reported a correlation between Simon costs and language switch costs to the L1, suggesting that language switching and non-linguistic inhibition are indeed related. To further investigate the relationship between language switching and domain-general inhibition, our participants performed two tasks that have been argued to reflect inhibition skills (Simon task and stop-signal task; cf., Van den Wildenberg et al., 2010). We expected to find a correlation between language switch costs and performance on the Simon and stop-signal tasks.

As a third aim, we intended to address the influence of language proficiency on inhibition by comparing two non-native languages of different proficiency levels. We therefore tested trilingual participants in Dutch (L1), English (L2), and German (L3). In this way, the influence of non-native language proficiency on language switching could be tested directly within participants.

Methods

All participants first took part in a behavioural picture naming experiment, which was followed by three measures of executive control and working memory. In the Simon task (cf., Bialystok et al., 2004), participants had to respond to shapes presented on the right or left side of the screen. On congruent trials, the required response button matched the presentation side on the screen (e.g., left button with left side). On incongruent trials, there was a mismatch between response button and presentation side (e.g., right button with left side). Response time and accuracy were measured. In the stop-signal task (Verbruggen et al., 2008) participants had to respond to the presentation of a square or a circle by pressing a corresponding button. In 25% of the trials, however, participants heard an auditory stimulus, indicating they had to inhibit their response. The stop-signal reaction times (SSRT) were taken as a measure of inhibition. The operation span task (cf., Conway et al., 2002) was used to measure working memory capacity. Participants had to solve math equations while remembering sequences of words. Language proficiency in all three languages was measured with LexTALE (Lemhöfer and Broersma, 2012), and the Boston Naming Test (BNT, Kaplan et al., 1983). Approximately three months after the behavioural experiment, the same participants performed the picture naming task in the MRI scanner.

Participants

During the behavioural experiment, 27 students of the Radboud University Nijmegen participated in return for either course credits or payment. All participants were right-handed Dutch (L1) native speakers with good proficiency in English (L2) and intermediate proficiency in German (L3). All participants had normal or corrected-to-normal vision and none had any neurological, reading or hearing impairment. All participants gave informed consent. The data of three participants were excluded because they had either an insufficient level of proficiency in German (two participants) or high error rates (>33.3%) in the picture naming task (one participant). The final sample of the behavioural experiment consisted of 24 subjects, 19 female, aged from 18 to 27 years ($M = 22.22$ years; $SD = 3.89$). A subset of 18 participants took part in the fMRI experiment. One participant was excluded from further analyses as she did not finish the experiment. The final sample consisted of 17 participants, 12 female, aged from 18 to 25 years ($M = 21.82$; $SD = 2.30$). Table 1 shows the L2 and L3 Age of Acquisition (AoA) according to an online self-rating questionnaire, the self-rated number of hours of language use (5-point scale: 1 = 'less than 1 h per week'; 5 = 'more than 10 h per week'), and self-rated language skills (7-point scale: 1 = 'very poor'; 7 = 'very good'). Furthermore, Table 1 shows the average scores per language in the Boston Naming Test (maximum score 60 points) and LexTALE (maximum score 100 points). All languages differed significantly from each other, in the expected

Table 1
Mean and standard deviation (between brackets) of the measures of the subjects' language backgrounds, self-ratings, and proficiency tests.

	L1 (Dutch)	L2 (English)	L3 (German)
Self-rating			
AoA		10.00 (1.94)	12.59 (0.94)
Hours per week	5.00 (0.00)	3.30 (1.34)	2.30 (1.73)
Listening	6.41 (.87)	5.71 (.77)	5.00 (.94)
Reading	6.76 (.44)	6.00 (.71)	4.82 (1.07)
Writing	6.47 (.62)	5.00 (.71)	3.65 (1.06)
Speaking	6.66 (.62)	5.35 (.79)	4.41 (.94)
Vocabulary	6.53 (.72)	5.35 (.61)	4.00 (1.27)
Proficiency test			
LexTALE	88.59 (8.49)	77.59 (12.80)	64.12 (6.65)
Boston Naming Test	53.43 (3.61)	38.57 (5.92)	20.50 (6.22)

order (L1 Dutch, L2 English, L3 German), in terms of AoA, self-ratings, and language proficiency tests.

Picture naming task

Materials and apparatus

The same stimuli were used during the behavioural and the fMRI experiment. Eighteen line drawings were selected from the picture database from the Max Planck Institute. The pictures depicted high frequent, concrete objects, and the picture names were matched on the number of syllables, phonemes, and L1 frequency (based on the CELEX database, Baayen et al., 1995). None of the picture names were identical cognates or false friends across the three languages (see Supplementary materials Table S1 for stimulus materials). Each participant received a different pseudorandom list of stimuli. Stimuli were presented at the centre of a white background and had a size of 80 mm wide and 80 mm long. The presentation of the stimuli was controlled by Presentation Software (Neurobehavioral Systems, Albany, CA, USA).

Design and procedure

The experiment consisted of a blocked and a mixed naming part. In the blocked part, participants named the pictures in their L1, L2, and L3 separately, with the order of the languages counterbalanced across participants. During the mixed context, participants named successive pictures in their L1, L2, or L3 according to a colour cue. In this context, one-third of the trials were non-switch trials (naming language of two or more subsequent trials is the same) and two-third were switch trials (naming language of the current trial differs from the previous trial). Switch and non-switch trials were presented in a random order. There were, thus, three possible non-switch types (L1–L1; L2–L2; L3–L3) and six possible switch types (L2–L1; L3–L1; L1–L2; L3–L2; L1–L3; L2–L3). In total, participants named 90 trials in the blocked context (30 per language) and 270 in the mixed context (90 per language).

A trial started with the presentation of a fixation cross for 500 ms (see Fig. 1), followed by a picture stimulus. This stimulus was presented for 2750 ms and then followed by a jittered interval of 4 to 6 s to improve the sampling of the slow BOLD-response. Voice onset times were measured with the inbuilt voicekey function of presentation and responses were recorded with a noise cancelling microphone. Voice onset times were checked manually to ensure that they reflected the onset of speech rather than the RF pulse of the MRI scanner. The voice recording started at the presentation of the picture and naming times were only recorded during the 2750 ms the picture was on the screen. Each picture was surrounded by a colour frame that indicated the language in which participants had to name the picture (e.g., red — Dutch). Each language was combined with two different colours to avoid confounds between cue and language switching. Thus, the colour cue always changed between two subsequent trials, even if participants did not have to switch between languages. Although participants did not need the colour cue to select the language in the blocked context, the colour frame was present in both blocked and mixed naming to minimize differences between the two contexts.

Participants received written instructions before the start of the experiment, asking them to name each picture as fast and as accurately as possible, while minimizing head movements. They also received a booklet with the 18 pictures and corresponding Dutch, English, and German names to familiarize themselves with the stimulus set and, thus, to diminish the number of errors in the picture naming experiment. After the instruction phase, participants were positioned in the scanner and named the pictures in the blocked context (90 trials). The blocked context (lasting approximately 15 min) was followed by the T1-scan (lasting 10 min). Next, the mixed picture naming task started, lasting approximately 45 min. The order of blocked versus mixed context was not counterbalanced to avoid local inhibition from the mixed context interfering in the blocked context (cf., Guo et al., 2011). The duration of the entire fMRI experiment was 105 min (90 min scanning time).

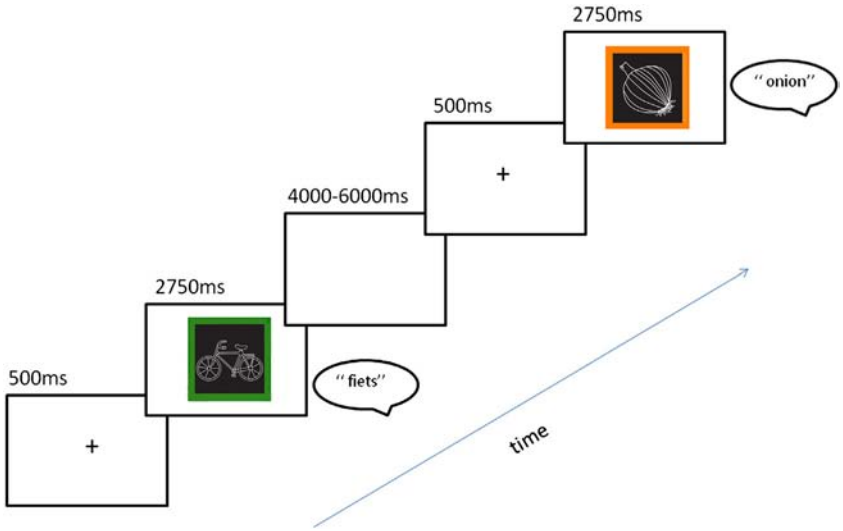

Fig. 1. Example of a trial sequence in the mixed context of the picture naming experiment. Here, the green frame indicates that the picture has to be named in L1 (Dutch), whereas the orange frame indicates that the picture has to be named in the L2 (English).

The entire behavioural experiment lasted 90 min: 45 min for the picture naming task and 45 min for the executive control and proficiency tasks.

FMRI data acquisition

Participants were scanned in a Siemens 1.5 T MRI scanner. For the functional MRI data, we used a multi-echo echo-planar imaging sequence (Poser et al., 2006) to reduce motion artefacts due to the language production task. Images were acquired at multiple time echoes (TEs) following a single excitation (time repetition (TR) = 2250 ms; each volume consists of 35 slices of 3.0 mm slice thickness with a slice gap of 17%; isotropic voxel size = 3.5 × 3.5 × 3.0 mm; field of view (FOV) = 224 mm). The functional images were acquired at TE 1 = 8.3 ms; TE 2 = 27.6 ms; TE 3 = 37 ms; TE 4 = 46 ms; TE 5 = 55 ms. For each subject, the first six volumes in each scan series were discarded as magnetization had not yet reached the equilibrium state. The anatomical images were acquired using a T1-weighted three-dimensional gradient-echo sequence (TR = 2300 ms; TE = 3.03 ms; FOV = 256 mm; 192 sagittal slices).

FMRI data analysis

We used SPM8 (Wellcome Department of Cognitive Neurology, London, UK) for image processing and statistical analysis. Image processing included realignment, slice timing correction, anatomic-functional image co-registration, segmentation, normalisation, and smoothing with a Gaussian filter of 8 mm full width at half maximum. A General Linear Model was used to estimate the effect of context for each individual subject. All contrasts were averaged, so that the two sides of the comparison were weighted equally. Naming latencies were included as a regressor of no interest. For each subject and context, significant changes in the BOLD response were assessed using *t*-statistics. The group averaged effects were computed with a random effects model. For group analysis, clusters with more than 10 voxels activated above a threshold of $p < 0.05$ (FWE, corrected for multiple comparisons) were considered significant. The naming latencies of both the behavioural as well as the fMRI experiment did not show any differences between the L2 and L3. Therefore, we grouped the non-native languages (L2/L3) to compare them to the native language (L1) in the fMRI analysis. In the contrasts, trials were weighted so that the L2 and L3 together received an equal weight compared to L1. Differences in activation were thus not due to differences in the number of trials.

To examine the brain mechanisms underlying local inhibition, we conducted two main analyses on the fMRI data: Switch versus non-switch and mixed versus blocked. Within the mixed context, we contrasted switch to non-switch trials and specifically L2/L3 switch trials > L2/L3 non-switch trials and L1 switch trials > L1 non-switch trials. We also examined the main effect of language by contrasting L2/L3 mixed naming > L1 mixed naming. We furthermore compared the mixed to the blocked context.[1] To specifically address local inhibition, we also compared the mixed switch trials to the blocked context: L2/L3 mixed switch > L2/L3 blocked; L1 mixed switch > L1 blocked. Based on previous studies (Jahfari et al., 2011; Xue et al., 2008), two cortical brain regions (rIFG and pre-SMA) related to inhibition were defined as ROIs.[2] ROIs were generated based on previously reported MNI coordinates (Jahfari et al., 2011) in the rIFG (centre = 51, 19, 17; 16 mm radius) and the pre-SMA (centre = 9, 24, 50; 8 mm radius). We used the MarsBar ROI Toolbox to investigate the BOLD responses in these ROIs for the above-named contrasts. Contrast values (effect sizes for the ROI) were obtained from the single-subject contrast images and were exported to SPSS for group level analyses. We used a repeated measures analyses of variance (ANOVA) to identify effects of language (L1, L2/L3), trial sequence (switch, non-switch), or context (blocked, mixed) on BOLD responses in the ROIs.

Results

Behavioural results

The earlier behavioural experiment showed the same effects as the fMRI experiment. Here, we only report the results of the behavioural data of the fMRI experiment (see Supplementary materials Table S2 for the behavioural experiment). We only included naming latencies of correct trials in the analysis. Trials were incorrect if A) there was no response; B) the response was given too late; C) the response was given in the wrong language and on the trial following language-selection errors; D) there were hesitations or the wrong word in the correct language was selected; and E) there were recording failures or naming latencies shorter than 300 ms. The experimental design included two main within-subject factors: Language (L1, L2, L3) and context (blocked, mixed). The mixed context furthermore contained the within-subject factor trial sequence (switch, non-switch trials). Error rates and naming latencies were submitted to repeated measures ANOVA for subjects (F_1) as well as items (F_2). We used an alpha level of .05 for all statistical tests. The accuracy rates followed the same pattern as the naming latencies and we therefore only report the naming latencies here (for accuracy rates, see Supplementary materials Table S3 and S4). We first analysed the naming latencies in the blocked and mixed contexts separately (see Supplementary materials Table S3), before comparing switch to non-switch trials and the mixed to the blocked context.

Blocked and mixed context

In the blocked context, there was a significant effect of language, $F_1(2, 32) = 12.65$, $p < .001$, $\eta_p^2 = .44$; $F_2(2, 34) = 10.40$, $p < .001$, $\eta_p^2 = .38$. Naming latencies thus differed among the three languages in the blocked context. A further comparison of the individual languages showed a significant difference in naming latencies between L1 and L3, $F_1(1, 16) = 25.88$, $p < .001$, $\eta_p^2 = .62$; $F_2(1, 17) = 12.89$, $p = .002$, $\eta_p^2 = .43$, and between L1 and L2, $F_1(1, 16) = 17.81$, $p = .001$, $\eta_p^2 = .53$; $F_2(1, 17) = 15.56$, $p = .001$, $\eta_p^2 = .48$. Between L2 and L3, however, there was no significant difference, $F_1(1, 16) = .99$, $p = .34$; $F_2(1, 17) = .05$, $p = .82$. Naming in L1 (1150 ms) was faster than naming in L2 (1267 ms) or L3 (1301 ms). Pictures were named equally fast in L2 and L3. The mixed context showed no significant main effect of language, $F_1(2, 32) = .84$, $p = .44$; $F_2(2, 34) = 3.88$, $p = .065$. Whereas the L1 was named faster than the L2 and L3 in the blocked context, all languages were named equally fast in the mixed context (L1 = 1589 ms; L2 = 1560 ms; L3 = 1535 ms).

Switch versus non-switch trials

Within the mixed context, we compared switch to non-switch trials to test for effects of inhibition (see Fig. 2 and Supplementary materials Table S4). Switch trials (1581 ms) were significantly slower than non-switch trials (1521 ms), $F_1(1, 16) = 11.62$, $p = .003$, $\eta_p^2 = .70$; $F_2(1, 17) = 15.70$, $p = .001$, $\eta_p^2 = .84$. There was no interaction of trial

[1] There is some confusion in the literature regarding the definition of global versus local inhibition related to mixed versus blocked naming. Whereas Guo et al. (2011) defined mixed versus blocked naming as *local* inhibition, others (e.g., Gollan and Ferreira, 2009; Prior and MacWhinney, 2010) have used the term *global* to refer to differences between mixed non-switch trials and blocked trials. In this sense, a general comparison between mixed and blocked naming would involve both global (non-switch mixed vs. blocked) and local inhibition (switch mixed vs. blocked). We therefore analysed our fMRI data in two ways. We first compared the mixed versus blocked context as a whole, following the definition of local inhibition by Guo et al. (2011), and then only compared switch trials to blocked naming to focus on local inhibition.

[2] Some studies have also found inhibition-related activity in the STN. Because Xue et al. (2008) did not find activation in this area during speech inhibition, we only included the rIFG and pre-SMA in our ROI analysis.

Fig. 2. Mean naming latencies per language as a function of trial sequence (non-switch, switch).

sequence (switch, non-switch trials) and language (L1, L2, L3), $F_1(2, 32) = 2.83$, $p = 0.074$, $\eta_p^2 = .15$; $F_2(2, 34) = 1.17$, $p = .32$, $\eta_p^2 = .06$. The difference between switch and non-switch trials (i.e., the switch costs) thus did not differ significantly between L1 (97 ms), L2 (31 ms) and L3 (55 ms).

Mixed versus blocked

To examine whether there was a difference in inhibition between languages in the blocked and the mixed context, we tested for an interaction between context (blocked, mixed) and language (L1, L2, L3). Taking the two contexts together, there was a significant main effect of language in the item, but not subject analysis, $F_1(2, 32) = 1.93$, $p = .16$, $\eta_p^2 = .28$; $F_2(2, 34) = 3.39$, $p = .046$, $\eta_p^2 = .30$, and there was a significant main effect of context, $F_1(1, 16) = 86.80$, $p < .001$, $\eta_p^2 = .84$; $F_2(1, 17) = 103.32$, $p < .001$, $\eta_p^2 = .98$. Naming was slower in the mixed context (1561 ms) than in the blocked context (1239 ms). Importantly, there was a significant interaction between context and language, $F_1(2, 32) = 8.70$, $p = .001$, $\eta_p^2 = .52$; $F_2(2, 34) = 27.96$, $p < .001$, $\eta_p^2 = .74$. The difference between naming in the mixed context minus naming in the blocked context was larger for L1 (356 ms) than for L2 (293 ms) and L3 (234 ms), suggesting that the difference in inhibition between the blocked and mixed context is larger for L1 than for L2 and L3 (see Fig. 3).

Executive control and proficiency results

Simon costs showed a trend in predicting L1 switch costs, $\beta = -1.51$, $t(11) = -1.84$, $p = .086$ (see Supplementary materials Fig. S1). This relationship was negative: The higher the Simon costs, the less time participants needed to switch to L1. Thus, the better participants performed in the Simon task, the more they inhibited the L1 and consequently the larger the switch cost to L1. Simon costs were a significant predictor of L2 switch costs, $\beta = .70$, $t(11) = 3.8$, $p = .002$. This relationship was positive: The higher the Simon costs, the more time participants needed to switch to the L2. Similarly, Simon costs were a significant predictor of L3 switch costs, $\beta = .60$, $t(11) = 2.89$, $p = .012$. This relationship was positive: The higher the Simon costs, the more time participants needed to switch to the L3. Performance on the stop-signal task, operation span, or proficiency scores was not a significant predictor of L1, L2, or L3 switch costs.

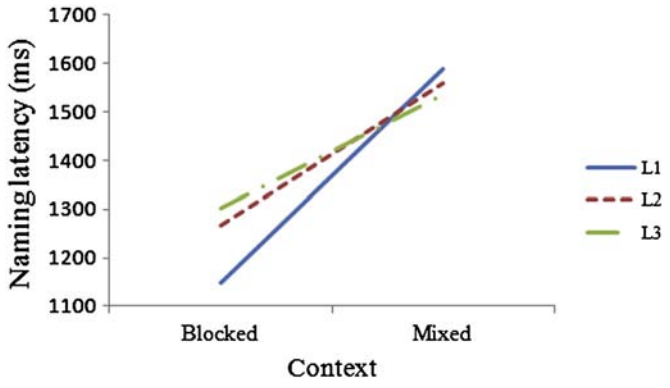

Fig. 3. Mean naming latencies per language as a function of context (blocked, mixed).

FMRI data

We first report the ROI analysis for the rIFG and pre-SMA, followed by the whole-brain analysis.

ROI analysis

Switch versus non-switch trials. We expected that the difference in inhibition between switch and non-switch trials within the mixed context would be larger for L2/L3 than for L1. A repeated measures ANOVA with language and trial sequence showed no significant effect of language ($p > .05$ in rIFG and pre-SMA) or trial sequence ($p > .05$ in rIFG and pre-SMA). Importantly, however, there was a significant interaction of language by trial sequence for both the rIFG, $F(16) = 8.44$, $p = .010$, $\eta_p^2 = .35$, and the pre-SMA, $F(16) = 11.09$, $p = .004$, $\eta_p^2 = .41$. This interaction suggests a difference between languages in terms of inhibition in switch trials compared to non-switch trials.

We therefore analysed the differences between switch and non-switch trials for the L2/L3 and L1 separately. Comparing switches to L2/L3 to L2/L3 non-switches showed significantly more activation in the rIFG, $F(16) = 10.29$, $p = .005$, $\eta_p^2 = .39$, and the pre-SMA, $F(16) = 5.57$, $p = .031$, $\eta_p^2 = .26$, see Fig. 4A.[3] Thus, there was more activation in the inhibition areas for switches to L2 and L3 compared to non-switches in L2 and L3. Comparing L1 switches to L1 non-switches, however, did not reveal significant differences in activation in the rIFG, $F(16) = 3.05$, $p = .10$, and marginally in the pre-SMA, $F(16) = 3.46$, $p = .081$. To summarize, switches to L2/L3 showed significantly more activation in the inhibition areas compared to L2/L3 non-switch trials. However, L1 switching did not show increased activation compared to L1 non-switch trials (see Fig. 4A).

In the above analysis, we collapsed L2 and L3 trials regardless of the language of the previous trial. We thus not only compared L1–L2 and L1–L3 switches versus non-switch trials, but also included L2–L3 and

[3] Similar results were found when we compared the two non-native languages separately. Switches to L2 compared to L2 non-switches showed increased activation in the rIFG, $F(16) = 5.75$, $p = .029$, $\eta_p^2 = .26$, although not in the pre-SMA, $F(16) = 1.29$, $p = .27$, $\eta_p^2 = .08$, and more activation was obtained for switches to L3 compared to L3 non-switches: rIFG, $F(16) = 7.47$, $p = .015$, $\eta_p^2 = .32$; pre-SMA, $F(16) = 4.46$, $p = .050$, $\eta_p^2 = .22$.

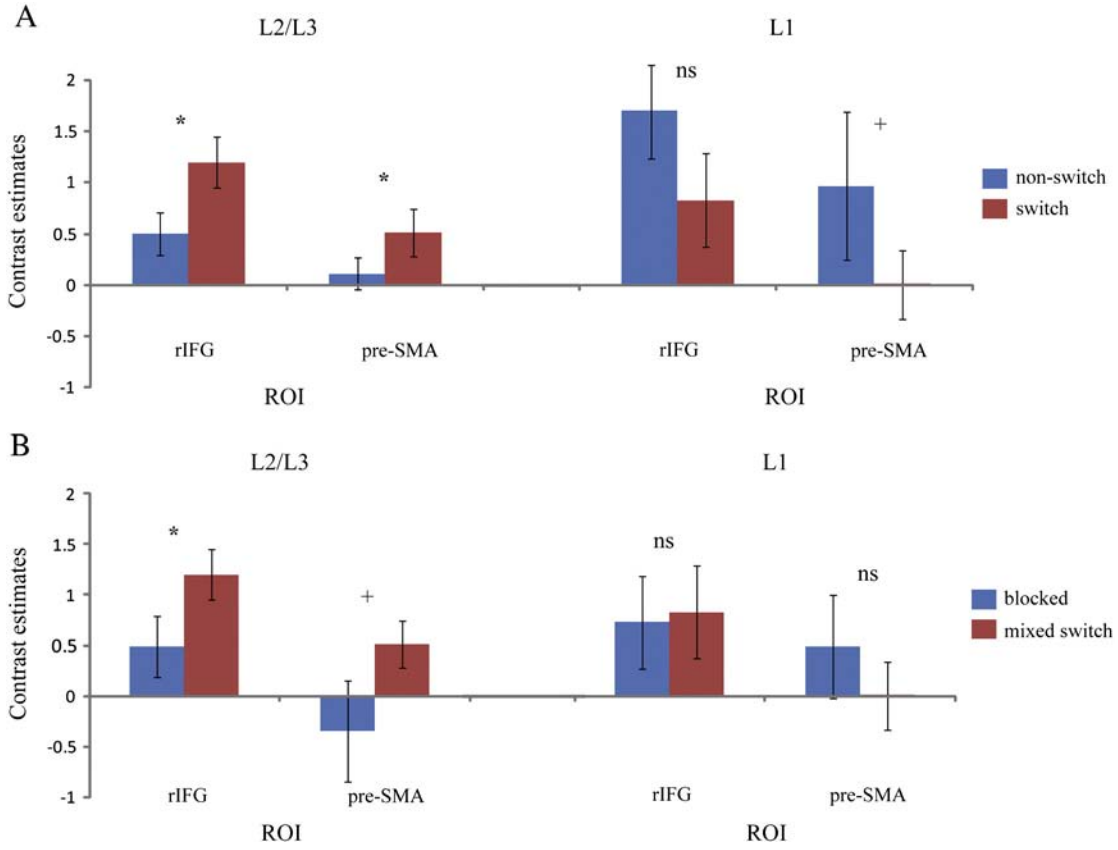

Fig. 4. Results from the ROI analysis. The graphs show the contrast estimates for the two ROIs (left: rIFG; right: pre-SMA). Error bars show the standard error of the mean. *: $p < .05$; +: $p < .1$; ns: $p > .1$. (A). Contrast estimates for switch trials compared to non-switch trials. The left panel depicts the difference for L2/L3; the right panel for L1. (B). Contrast estimates for mixed switch trials compared to blocked trials. The left panel depicts the difference for the L2/L3; the right panel for the L1.

L3–L2 trials. The IC model (Green, 1998), however, argues that the L1 in particular needs to be inhibited. To make sure that the effect is indeed driven by inhibition-related activity for the L1 in particular, we conducted the same ANOVA with language and trial sequence, but now only included L1–L2 and L1–L3 switch trials. This analysis yielded the same results, with no main effect of language or trial sequence ($p > .05$ in rIFG and pre-SMA), but again a significant interaction was found for the rIFG, $F(16) = 13.30$, $p = .002$, $\eta_p^2 = .45$, and the pre-SMA, $F(16) = 14.98$, $p = .001$, $\eta_p^2 = .48$.

We then analysed the differences between L1 and L2/L3 for the non-switch and switch trials separately. For the non-switch trials only, there was no effect of language ($p > .05$ in rIFG and pre-SMA). For the switch trials only, there was a main effect of language. Switches to L2/L3 compared to switches to L1 showed more activation in the rIFG, $F(16) = 5.68$, $p = .030$, $\eta_p^2 = .26$, and in the pre-SMA, $F(16) = 6.56$, $p = .021$, $\eta_p^2 = .29$.[4] Compared to L1 switching, there was thus more activity in inhibition-related areas in switching to the non-native languages.

Mixed versus blocked. Following the definition of local inhibition by Guo et al. (2011), we first compared the entire mixed context (including switch and non-switch trials) to the blocked context. A repeated measures ANOVA with language (L1, L2/L3) and context (mixed, blocked) revealed no significant main effect of language ($p > .05$ in rIFG and pre-SMA) and a marginally significant effect of context in the rIFG, $F(16) = 4.30$, $p = .06$, but not in the pre-SMA, $F(16) = 3.37$, $p = .10$. There was no significant interaction between language and context ($p > .05$).

We then compared switch trials only to blocked naming to test for local inhibition. Again, there was also no significant main effect of language or context ($p > .05$ in rIFG and pre-SMA). However, there was a marginally significant interaction between language and context in the rIFG, $F(16) = 3.37$, $p = .065$, $\eta_p^2 = .17$, and a significant interaction in the pre-SMA, $F(16) = 7.31$, $p = .016$, $\eta_p^2 = .31$. This interaction suggests a difference between languages in terms of inhibition in switch trials compared to blocked trials.

We therefore analysed the differences between switch trials and blocked trials separately for L2/L3 and L1 naming. L2/L3 mixed switch trials compared to L2/L3 blocked trials showed significantly more activation in the rIFG, $F(16) = 4.10$, $p = .045$, $\eta_p^2 = .27$, and a marginally significant effect in the pre-SMA, $F(16) = 4.00$, $p = .050$, $\eta_p^2 = .26$ (Fig. 4B).[5] Thus, there was more activation in the inhibition areas when switching to L2 and L3, compared to blocked naming in L2 and L3. Comparing L1 switch trials to L1 blocked trials did not yield significant differences in either the rIFG, $F(16) = .11$, $p = .74$, or the pre-SMA, $F(16) = .83$, $p = .38$ (Fig. 4B). This suggests that, compared to blocked naming, there was more inhibition-related activity in switch

[4] This difference remained significant when we further compared the two non-native languages to the L1 separately. Switches to L2 compared to switches to L1 showed more activation in the rIFG, $F(16) = 7.01$, $p = .018$, $\eta_p^2 = .31$, and pre-SMA, $F(16) = 4.73$, $p = .045$, $\eta_p^2 = .23$. Similarly, switches to L3 compared to switches to L1 showed more activation in the rIFG, $F(16) = 7.00$, $p = .017$, $\eta_p^2 = .30$, and marginally in the pre-SMA, $F(16) = 4.01$, $p = .063$, $\eta_p^2 = .20$.

[5] Similar results were found when the L2 and L3 were analysed separately. Switches to L2 > L2 blocked: rIFG, $F(16) = 8.22$, $p = .011$, $\eta_p^2 = .34$; pre-SMA, $F(16) = 3.07$, $p = .065$, $\eta_p^2 = .11$; Switches to L3 > L3 blocked: rIFG, $F(16) = 4.23$, $p = .056$, $\eta_p^2 = .21$, pre-SMA, $F(16) = 4.73$, $p = .040$, $\eta_p^2 = .15$.

trials to L2 and L3. However, for the L1, the same amount of inhibition-related activity was found for mixed switching and blocked naming.

Again, we tested the L1–L2 and L1–L3 switch trials only to make sure that the interaction was driven by inhibition of the L1 in particular. This model yielded the same results, with no main effect of language or trial sequence ($p > .05$ in rIFG and pre-SMA), but again a significant interaction for the rIFG, $F(16) = 6.63$, $p = .020$, $\eta_p^2 = .29$, and the pre-SMA, $F(16) = 11.37$, $p = .004$, $\eta_p^2 = .42$.

Whole-brain analysis

Switch versus non-switch trials. Taking all three languages together, there was no brain area showing a main effect of switch trials compared to non-switch trials on FWE corrected $p < .05$. Relative to non-switches in the L2/L3, however, switching to L2/L3 showed increased activation in the left precuneus (BA7), left MCC (BA24), right PCC (BA23), right cuneus (BA17), and the right ACC (BA24) (Table 2, Fig. 5A). Switching to L1 compared to non-switches in L1 did not show significant activation differences.

We also found a main effect of language in several brain areas when we compared L2/L3 naming to L1 naming (see Fig. 5B and Supplementary materials Table S5). Relative to naming in L1, naming in L2 and L3 activated the left IFG (BA45); left pre-SMA (BA6); right SMA (BA6); left pre-/postcentral gyrus (BA44/6); right Heschl's gyrus (BA41), right postcentral gyrus (BA6), and right insula (BA13); bilateral MCC (BA6); left calcarine gyrus (BA17) and cerebellum; right inferior occipital gyrus (BA19), bilateral putamen and right caudate nucleus; and right cerebellum. Relative to the L2 and L3, naming in L1 did not show significant activation differences.

Mixed versus blocked. Taking the switch and non-switch trials together, the mixed context compared to the blocked context did not show significant activation differences in any brain area on FWE corrected $p < .05$. Similarly to the ROI analysis, we then compared the switch trials to blocked naming in L2/L3, which showed a significant effect in the right MFG (BA46), the right ACC (BA24), and the left precuneus (BA7) (Table 3, Fig. 5C). Switching to L1 in mixed naming compared to L1 blocked naming did not show significant activation differences.

Differences between L2 and L3

Besides the comparison between native and non-native languages, we also compared the L2 and L3 in both the ROI analysis and the whole-brain analysis. We did not observe any differences between L2 and L3, either when comparing switch to non-switch trials or when comparing mixed to blocked naming (all p values >0.05 for both rIFG and pre-SMA). In the whole-brain analysis, we did not even observe differences between L2 and L3 when we lowered the threshold to uncorrected $p < 0.001$.

Table 2
Brain regions activated when contrasting switch trials with non-switch trials ($p < .05$, $k > 10$ voxels, FWE corrected). Multiple peaks in different brain regions within a single activation cluster are shown indented; Z refers to the highest Z score within that region. MCC = middle cingulate cortex; PCC = posterior cingulate cortex; ACC = anterior cingulate cortex.

Brain region	BA	Cluster size	MNI coordinates			Z value
			x	y	z	
L2/L3 switches > L2/L3 non-switches						
Precuneus, cingulate cortex		1251				
L precuneus	7		−8	−74	36	4.71
L MCC	24		−4	−34	38	4.41
R PCC	23		4	−28	28	4.65
R cuneus	17		22	−66	24	4.71
R ACC	24	242	4	24	28	4.72
L1 switches > L1 non-switches						
No significant activation differences						

Simon costs

We also analysed the correlation between Simon costs and activation in the inhibition areas from the ROI analysis. There was a trend towards a negative correlation between the Simon costs and activation in the inhibition areas for switch costs (switch trials–non-switch trials) in the L2 and L3 (rIFG, $r = -.28$, $p = .14$; pre-SMA, $r = -.42$, $p = .055$). The lower the Simon costs (reflecting better inhibition skills), the more activation was found in the rIFG and pre-SMA on L2/L3 switch compared to non-switch trials.

Discussion

The prevailing theory of language switching states that unbalanced bilinguals use inhibition to switch between their languages (Green, 1998). The present fMRI study investigated whether the brain mechanisms underlying trilingual language switching are indeed inhibitory or are rather related to other aspects of executive control. To test this, unbalanced trilinguals performed a picture naming task in the MRI scanner. Our results provide evidence that language switching recruits both brain areas related to inhibition as well as areas associated with non-inhibitory aspects of executive control. We first discuss the behavioural results and the fMRI data for switch versus non-switch trials and for mixed versus blocked naming. Together, these results shed more light on the role of domain-general inhibition areas in language switching. Second, we focus on the relationship between language switching and the Simon task. Third, we address switching to L2 versus to L3. Finally, we discuss the main theoretical implications.

Domain-general inhibition in switching versus non-switching

Within the mixed condition, we compared switch versus non-switch trials. The behavioural data showed that non-switch trials were named faster than switch trials, but we did not observe a clear asymmetry in switch costs, contrary to other studies with unbalanced bilinguals (e.g., Costa and Santesteban, 2004; Meuter and Allport, 1999). The absence of asymmetrical switch costs is often taken as evidence for the absence of inhibition too. In our fMRI data, however, we find evidence suggesting that language switching is, at least partly, achieved by inhibitory mechanisms. We found more activation in the rIFG and pre-SMA in switches to the weaker L2 and L3 compared to non-switches, but this difference was absent for the L1. The rIFG and pre-SMA are often reported to be involved in inhibition (cf., Aron, 2007; Aron et al., 2004a,b; Forstmann et al., 2008; Jahfari et al., 2011; Van den Wildenberg et al., 2010). Differences in activation in these areas are therefore suggested to reflect differences in inhibition. The activation differences for L2/L3 indicate that switches to weaker, non-native languages require more inhibition-related activity than non-switch trials. The absence of such a difference for the L1 shows that L1 switch and non-switch trials are accompanied by an equal amount of activation in areas related to inhibition. These findings are compatible with Green's IC model (1998), as inhibition seems to be modulated by the strength of the language. Picture naming in the strong L1 does not require inhibition of the weaker languages, regardless of the trial type. For weaker languages, however, more inhibition of the L1 is needed for switch trials than for non-switch trials.

Thus, we find an effect of switching in inhibition-related brain areas in the absence of clear asymmetrical behavioural switch costs. This suggests that (the absence of) behavioural asymmetrical switch costs cannot be taken as a reliable indicator of inhibition. The conclusions of Costa and Santesteban (2004) are therefore not compatible with our findings. Based on symmetrical switch costs, they concluded that balanced bilinguals do not use inhibition. Our study show otherwise: Even in the

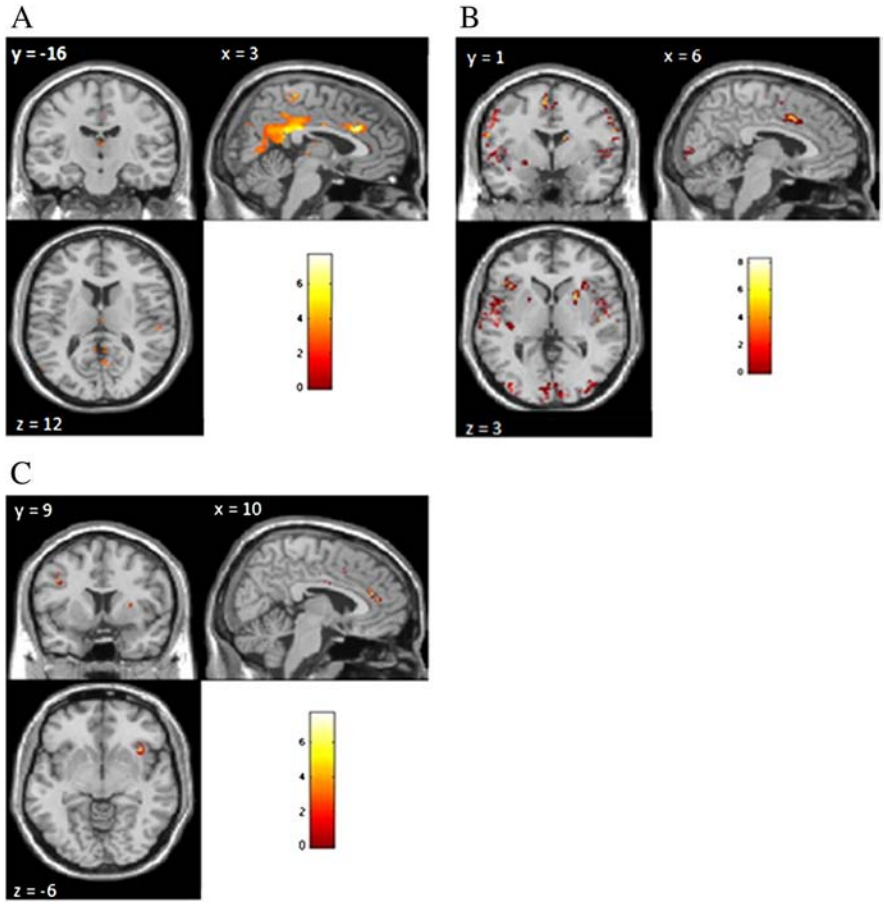

Fig. 5. Whole-brain analysis. (A). Switches to L2/L3 compared to L2/L3 non-switch trials. (B). Mixed naming in L2/L3 compared to mixed naming in L1. (C). Mixed switches to L2/L3 compared to blocked naming in L2/L3. Colour bars indicate Z-score.

absence of asymmetrical switch costs, language switching can still involve inhibition.

Contrary to our predictions, however, switch trials in general did not show more activation in the rIFG and pre-SMA than non-switch trials. The absence of this effect is likely to be related to L1 non-switch trials. Whereas L2/L3 *switch* trials showed more activation than *non-switch* trials, there was also slightly more activation in L1 *non-switch* trials than in switch trials. It is likely that these opposing effects for L2/L3 and L1 prevented the difference between switch and non-switch trials in general from reaching significance. The increased activation for L1 non-switch trials, albeit non-significant, is surprising, but might be related to the larger percentage of switch compared to non-switch trials in our experiment. An L1 switch trial was followed by L1 non-switch trials in only one-third of the cases, but by L2 or L3 switch trials in two-third of the cases. The relatively large chance of having to switch to L2 or L3 might have led participants to 'pre-activate' the rIFG and pre-SMA, even if the next trial appeared to be a L1 non-switch trial. This explanation, however, is speculative and more research is needed to investigate this issue.

Table 3
Brain regions activated when contrasting switch trials with blocked naming trials ($p < .05$, $k > 10$ voxels, FWE corrected). Z refers to the highest Z score within that region. MFG = middle frontal gyrus; ACC = anterior cingulate cortex.

Brain region	BA	Cluster size	MNI coordinates			Z value
			x	y	z	
L2/L3 mixed switches > L2/L3 blocked naming						
R MFG	46	13	38	52	20	4.46
R ACC	24	41	4	42	12	5.70
L precuneus	7	23	−8	−66	32	4.71
L1 mixed switches > L1 blocked naming						
No significant activation differences						

Our results indicate that domain-general inhibition areas are involved in language switching, particularly in switches to non-native languages. Other brain areas related to different aspects of executive control were activated too. For switches to L2/L3 compared to L2/L3 non-switch trials, we observed a difference in activation in the ACC and in a cluster comprising the precuneus, cuneus, MCC, and PCC. Activation in the ACC likely reflects the increase in non-inhibitory aspects of executive control that are needed for switch trials. ACC activation is often reported in language switching (e.g., Hosoda et al., 2012; Wang et al., 2007). Furthermore, this area is a vital part of the language switching network proposed by Abutalebi and Green (2008). The (pre)cuneus is also often found in language switching studies (Guo et al., 2011; Wang et al., 2007), but its role remains unclear. The MCC and PCC have been found in various cognitive tasks too and have been linked to response selection and error detection (cf., Torta and Cauda, 2011, for a meta-analysis on the cingulate cortex).

Within the mixed condition, we also compared L2/L3 naming to L1 naming. Within the switch trials, we observed more activation in the rIFG and pre-SMA for switches to L2 and L3 compared to switches to L1, suggesting that switching to L2 and L3 requires more inhibition than switching to L1. We also observed other differences in brain activation between L2/L3 naming and L1 naming. Naming in the L2/L3 versus L1 naming showed activation in various brain regions, including the left IFG; bilateral (pre-)SMA; left pre-/postcentral gyrus; bilateral MCC; left calcarine gyrus and right inferior occipital gyrus; bilateral putamen and right caudate nucleus; and bilateral cerebellum. Activation in the visual areas could be related to an increase in visual attention to the colour or

picture during naming in the weaker languages. Activation in the precentral gyrus is often found in switching to a weaker language (Hernandez et al., 2000; Wang et al., 2007) and might be associated with phonological retrieval or encoding (Indefrey and Levelt, 2004). Similarly, the increased activation in the cerebellum might reflect a greater need for articulatory control in L2/L3 versus L1 (Booth et al., 2007). The putamen and caudate nucleus are part of the language switching network proposed by Abutalebi and Green (2008). The putamen has been suggested to be involved in motor control of weaker languages (Abutalebi et al., 2013b). However, the role of the right caudate nucleus in language switching has been debated. Most studies (e.g., Abutalebi et al., 2008; Crinion et al., 2006) report increased activation in the left or bilateral caudate nucleus during language switching. Wang et al. (2007), on the other hand, also found right lateralized activation. The present study supports the latter finding that the right caudate nucleus might be involved in language switching too.

Summarizing, our data show that switching compared to non-switching in a mixed context recruits areas related to inhibition and areas related to other aspects of executive control, like the ACC. These areas show an increase in activation for switches to the weaker L2 and L3 compared to non-switch trials, but no such difference was found for the L1. Similarly, more activation in both inhibitory and non-inhibitory executive control areas was found for switches to L2/L3 compared to switches to L1.

Domain-general inhibition in mixed versus blocked naming

The behavioural data showed a difference between blocked and mixed naming across the three languages. In the blocked context, naming was faster and more accurate in L1 compared to L2 and L3. In the mixed context, this effect disappeared: Naming was equally fast in all three languages. The difference between mixed and blocked naming was larger for L1 than for L2 and L3. This replicates other behavioural results (e.g., Christoffels et al., 2007) and is also compatible with the IC model, because it suggests that the L1 is inhibited more than the L2 and L3 in the mixed context compared to the blocked context. This is also compatible with our fMRI data that revealed more activation in the rIFG and pre-SMA for switches to L2/L3 compared to blocked trials, but no difference for the L1. This difference suggests that, relative to blocked naming, switches to weaker languages require more inhibition. These findings again support the IC model. In the blocked context, (relatively) little or no local inhibition is required. Similarly, little or no inhibition is expected for switches to the L1 in the mixed context. For switches to the L2 and L3, however, more local inhibition is needed, thus leading to differences between the blocked and the mixed switch trials. Again, we did not only observe differences in activation in inhibition areas, but also in other areas related to executive control. The whole-brain analysis showed increased activation in the right MFG, right ACC, and left precuneus for L2/L3 mixed compared to blocked trials. The MFG and ACC are included in the frontoparietal network that is linked to various aspects of executive control (Barbey et al., 2012; Collette et al., 2005; Niendam et al., 2012). This, again, reflects an increased need for executive control in L2/L3 trials in the mixed naming context. Contrary to our hypothesis, we did not observe a main effect of context in the rIFG and pre-SMA: In general, mixed naming did not require more inhibition than blocked naming. Still, there was a trend in this direction. We suspect that the large amount of variation across participants in terms of activation in the rIFG and pre-SMA prevented this effect from reaching significance. Furthermore, the blocked and mixed contexts were separated by the T1 scan, which might make a direct comparison less reliable.

In summary, our results show that switching to L2/L3 in the mixed context requires more activation of inhibition-related areas than L2/L3 blocked naming. No such difference was observed for the L1. Switching to L2/L3 compared to blocked naming also showed an increase in activation in areas related to non-inhibitory aspects of executive control, such as the ACC and MFG.

Relationship between language switching and simon task

Our results revealed a correlation between Simon costs (reflecting inhibition skills, cf., Van den Wildenberg et al., 2010) and both behavioural language switch costs as well as activation in the rIFG and pre-SMA. The correlation between Simon costs and L1 switch costs was negative: Better inhibition skills were associated with larger switch costs to the stronger language. In contrast, the correlation between Simon costs and L2/L3 switch costs was positive: Better inhibition skills were associated with smaller switch costs to weaker languages. Furthermore, there was a negative correlation between Simon costs and the amount of activity in the rIFG and pre-SMA in switches to L2/L3. This suggests that participants with better inhibition skills inhibit the L1 more when switching to the L2 and L3. This results in smaller switch costs to the L2 and L3, but in larger switch costs to the L1.

Two additional remarks must be made. First, our results are not compatible with those reported by Linck et al. (2012), who found a positive correlation between Simon costs and L1 switch costs and no correlation with L2/L3 switch costs. The direction of the correlation with L1 switch costs is thus reversed compared to our study. It is hard to explain this difference, but the additional correlation with the fMRI data in our study suggests that the amount of inhibition used in language switching is positively dependent on the participant's inhibition skills. Second, there was no correlation between performance on the stop-signal task and language switch costs. The stop-signal task is often taken as a measurement of inhibition and is also related to activation in the rIFG and pre-SMA. It is not clear why performance in this task did not show similar correlations as the Simon task. It could, however, be the case that both tasks tap into different aspects of inhibition. The inhibition in language switching might correspond better to the Simon task than the stop-signal task (cf., Colzato et al., 2008, for a discussion of different forms of inhibitory control in bilinguals).

Switching to L2 versus to L3

Our study did not find a difference between L2 and L3 naming. This is contrary to, for example, Schwieter (2013), who found an asymmetry in L2 and L3 behavioural switch costs. We also expected to find a difference between the L2 and L3, with more L1 inhibition and larger switch costs for the weaker L3. The difference in proficiency between L2 and L3 in our participants might have been too small to cause an effect. Furthermore, our participants learned both L2 and L3 for five or six years at high school. Therefore, the difference in Age of Acquisition was relatively small (2.5 years between L2 and L3) compared to other studies (e.g., Schwieter, 2013, reported a difference of 10.4 years). This small difference between L2 and L3 might have resulted in the absence of a proficiency effect in our study.

Theoretical implications

To summarize, our data show more activation in the rIFG and pre-SMA for switches to the L2 and L3 compared to non-switch and blocked trials. No such differences were found for the L1. Moreover, we also found greater activation in the rIFG and pre-SMA for L2 and L3 switches compared to L1 switches. Together, this suggests that language switching recruits domain-general inhibition areas, especially when switching to a weaker language. We furthermore observed correlations between language switching costs and Simon costs, also suggesting that language switching performance is linked to domain-general inhibition. Inhibition areas alone, however, are not sufficient. Switching to the L2 and L3 also recruited brain areas related to other aspects of executive control, such as the ACC, DLPFC, and striatum.

Our results thus show inhibition-related activity during language switching, which is modulated by language proficiency (i.e., L1 versus L2/L3). These findings are compatible with Green's IC model (1998). When participants have to switch to a weaker L2 and L3, the L1 has to be inhibited. This is reflected in an increased activation in the rIFG and pre-SMA for switches to L2/L3 compared to L2/L3 non-switch trials or L2/L3 blocked naming. The IC model is also supported by our finding that L2/L3 switch trials showed more activation in the rIFG and pre-SMA than L1 switch trials, suggesting that participants indeed showed more inhibition-related activity during switches to the weaker languages compared to the native language. Furthermore, this is reflected in the increased naming latencies in L1 in the mixed context compared to the blocked context. In the blocked context, the L1 is inhibited less and therefore L1 naming is faster. The relatively longer L1 naming latencies in the mixed condition are likely to reflect the time needed to overcome inhibition. Taken together, we thus obtained evidence supporting the two main predictions of the IC model (Green, 1998). First, our fMRI data suggest that switches to weaker languages require more inhibition of the strong L1 than vice versa. Second, our behavioural data partly suggest that it takes time to overcome this inhibition: In mixed versus blocked naming, but not in switch versus non-switch trials, we found larger costs for the L1 than for the L2 and L3. Together, these data support the theory that unbalanced bilinguals use inhibition in language switching.

Inhibition alone, however, is not sufficient for language switching. Abutalebi and Green (2008) proposed that a domain-general network for other aspects of executive control is also recruited during bilingual language switching. According to this model, language switching recruits the left prefrontal cortex, ACC, caudate nucleus, and parietal cortex. Our results are compatible with this model, because they indicate that areas like the ACC, striatum, and bilateral frontal cortices are indeed involved in language switching. This is also compatible with studies showing that the frontoparietal network represents different task features, such as colour cues, rules, and individual stimuli and responses (Woolgar et al., 2011). Our finding of increased activation in the rIFG combined with greater activation in other parts of the frontoparietal network is also compatible with the idea that the rIFG is not an isolated module, but plays a role in this larger network (cf., Dodds et al., 2011).

Our study is thus in line with the model proposed by Abutalebi and Green, especially the claim that language switching is achieved by domain-general mechanisms rather than language-specific networks. We also argue, however, that both this model and Luk's meta-analysis (2012) do not give a complete picture of the brain networks involved in language switching. Besides many areas related to non-inhibitory executive control, inhibition areas such as the rIFG and pre-SMA are also recruited during language switching. These areas that are particularly involved in inhibition are often not included in brain models of language switching. Our study, however, shows that these models should include, and distinguish between, areas related to inhibition in particular and to non-inhibitory aspects of executive control.

Conclusions

To our knowledge, our study is the first to specifically examine the involvement of domain-general inhibition areas in language switching. Our results indicate that language switching not only recruits brain regions that instantiate non-inhibitory aspects of executive control, but also areas related to inhibition in particular (i.e., rIFG and pre-SMA). This suggests that unbalanced bilinguals use inhibition in language switching, especially when they have to switch to their weaker languages. In this way, our study provides new and important neuroimaging evidence for the long-standing claim of the involvement of inhibition during language switching.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.neuroimage.2013.12.049.

Acknowledgments

We thank Paul Gaalman for his technical assistance during data collection.

Conflict of interest

The authors declare no conflict of interest.

References

Aarts, E., Roelofs, A., van Turennout, M., 2008. Anticipatory activity in anterior cingulate cortex can be independent of conflict and error likelihood. J. Neurosci. 28 (18), 4671–4678.
Abutalebi, D.J., Green, D.W., 2008. Control mechanisms in bilingual language production: neural evidence from language switching studies. Lang. Cogn. Process. 23 (4), 557–582.
Abutalebi, J., Annoni, J.M., Zimine, I., Pegna, A.J., Seghier, M.L., Lee-Jahnke, H., Khateb, A., 2008. Language control and lexical competition in bilinguals: an event-related fMRI study. Cereb. Cortex 18 (7), 1496–1505.
Abutalebi, J., Della Rosa, P.A.D., Ding, G., Weekes, B., Costa, A., Green, D.W., 2013a. Language proficiency modulates the engagement of cognitive control areas in multilinguals. Cortex 49 (3), 905–911.
Abutalebi, J., Della Rosa, P.A.D., Castro Gonzaga, A.K., Keim, R., Costa, A., Perani, D., 2013b. The role of the left putamen in multilingual language production. Brain Lang. 125 (3), 307–315.
Aron, A.R., 2007. The neural basis of inhibition in cognitive control. Neuroscientist 13 (3), 214–228.
Aron, A.R., Monsell, S., Sahakian, B.J., Robbins, T.W., 2004a. A componential analysis of task-switching deficits associated with lesions of left and right frontal cortex. Brain 127, 1561–1573.
Aron, A.R., Robbins, T.W., Poldrack, R.A., 2004b. Inhibition and the right inferior frontal cortex. Trends Cogn. Sci. 8 (4), 170–177.
Baayen, R.H., Piepenbrock, R., Gulikers, L., 1995. The CELEX Lexical Database [CD-ROM]. Linguistics Data Consortium, University of Pennsylvania, Philadelphia PA.
Barbey, A.K., Colom, R., Solomon, J., Krueger, F., Forbes, C., Grafman, J., 2012. An integrative architecture for general intelligence and executive function revealed by lesion mapping. Brain 135 (4), 1154–1164.
Bialystok, E., Craik, F.I., Klein, R., Viswanathan, M., 2004. Bilingualism, aging, and cognitive control: evidence from the Simon task. Psychol. Aging 19, 290–303.
Booth, J.R., Wood, L., Lu, D., Houk, J.C., Bitan, T., 2007. The role of the basal ganglia and cerebellum in language processing. Brain Res. 1133, 136–144.
Christoffels, I.K., Firk, C., Schiller, N.O., 2007. Bilingual language control: an event-related brain potential study. Brain Res. 1147, 192–208.
Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., Salmon, E., 2005. Exploring the unity and diversity of the neural substrates of executive functioning. Hum. Brain Mapp. 25, 409–423.
Colzato, L.S., Bajo, M.T., van den Wildenberg, W., Paolieri, D., Nieuwenhuis, S., Heij, W.L., Hommel, B., 2008. How does bilingualism improve executive control? A comparison of active and reactive inhibition mechanisms. J. Exp. Psychol. Learn. Mem. Cogn. 34 (2), 302.
Conway, A.R., Cowan, N., Bunting, M.F., Therriault, D.J., Minkoff, S.R., 2002. A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. Intelligence 30 (2), 163–183.
Cools, R., 2011. Dopaminergic control of the striatum for high-level cognition. Curr. Opin. Neurobiol. 21, 402–407.
Costa, A., Santesteban, M., 2004. Lexical access in bilingual speech production: evidence from language switching in highly proficient bilinguals and L2 learners. J. Mem. Lang. 50, 491–511.
Costa, A., Santesteban, M., Ivanova, I., 2006. How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. J. Exp. Psychol. Learn. Mem. Cogn. 32 (5), 1057–1074.
Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J.T., Aso, T., Urayama, S., Fukuyama, H., Stockton, K., Usui, K., Green, D.W., Price, C.J., 2006. Language control in the bilingual brain. Science 312 (5779), 1537–1540.
Dodds, C.M., Morein-Zamir, S., Robbins, T.W., 2011. Dissociating inhibition, attention, and response control in the frontoparietal network using functional magnetic resonance imaging. Cereb. Cortex 21 (5), 1155–1165.
Forstmann, B.U., Jahfari, S., Scholte, H.S., Wolfensteller, U., van den Wildenberg, W.P., Ridderinkhof, K.R., 2008. Function and structure of the right inferior frontal cortex predict individual differences in response inhibition: a model-based approach. J. Neurosci. 28 (39), 9790–9796.
Frank, M.J., 2011. Computational models of motivated action selection in corticostriatal circuits. Curr. Opin. Neurobiol. 21, 381–386.
Gollan, T.H., Ferreira, V.S., 2009. Should I stay or should I switch? A cost–benefit analysis of voluntary language switching in young and aging bilinguals. J. Exp. Psychol. Learn. Mem. Cogn. 35 (3), 640.
Graybiel, A.M., 2000. The basal ganglia. Curr. Biol. 10 (14), R509–R511.
Green, D., 1998. Mental control of the bilingual lexico-semantic system. Biling 1, 67–81.
Guo, T., Liu, H., Misra, M., Kroll, J.F., 2011. Local and global inhibition in bilingual word production: fMRI evidence from Chinese–English bilinguals. Neuroimage 56, 2300–2309.

Hermans, D., Bongaerts, T., De Bot, K., Schreuder, R., 1998. Producing words in a foreign language: can speakers prevent interference from their first language? Biling 1 (03), 213–229.
Hernandez, A.E., Martinez, A., Kohnert, K., 2000. In search of the language switch: an fMRI-study of picture naming in Spanish–English bilinguals. Brain Lang. 73, 421–431.
Hosoda, C., Hanakawa, T., Nariai, T., Ohno, K., Honda, M., 2012. Neural mechanisms of language switch. J. Neurolinguistics 25, 44–61.
Indefrey, P., Levelt, W.J., 2004. The spatial and temporal signatures of word production components. Cognition 92 (1), 101–144.
Jackson, G.M., Swainson, R., Cunnington, R., Jackson, S.R., 2001. ERP correlates of executive control during repeated language switching. Biling 4 (2), 169–178.
Jahfari, S., Waldorp, L., van den Wildenberg, W.P., Scholte, H.S., Ridderinkhof, K.R., Forstmann, B.U., 2011. Effective connectivity reveals important roles for both the hyperdirect (fronto-subthalamic) and the indirect (fronto–striatal–pallidal) fronto-basal ganglia pathways during response inhibition. J. Neurosci. 31 (18), 6891–6899.
Kaplan, E., Goodglass, H., Weintraub, S., 1983. The Boston Naming Test. Lea & Febiger, Philadelphia.
Kerns, J.G., Cohen, J.D., MacDonald, A.W., Cho, R.Y., Stenger, V.A., Carter, C.S., 2004. Anterior cingulate conflict monitoring and adjustments in control. Science 303 (5660), 1023–1026.
Lemhöfer, K., Broersma, M., 2012. Introducing LexTALE: a quick and valid lexical test for advanced learners of English. Behav. Res. Methods 44 (2), 325–343.
Linck, J.A., Schwieter, J.W., Sunderman, G., 2012. Inhibitory control predicts language switching performance in trilingual speech production. Biling 15 (3), 651–662.
Luk, G., Green, D.W., Abutalebi, J., Grady, C., 2012. Cognitive control for language switching in bilinguals: a quantitative meta-analysis of functional neuroimaging studies. Lang. Cogn. Process. 27 (10), 1479–1488.
Meuter, R.F.I., Allport, A., 1999. Bilingual language switching in naming: asymmetrical costs of language selection. J. Mem. Lang. 40, 25–40.
Niendam, T.A., Laird, A.R., Ray, K.L., Dean, Y.M., Glahn, D.C., Carter, C.S., 2012. Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. Cogn. Affect. Behav. Neurosci. 12 (2), 241–268.
Philipp, A., Gade, M., Koch, I., 2007. Inhibitory responses in language switching: evidence from switching language-defined response sets. Eur. J. Cogn. Psychol. 19 (3), 395–416.
Poser, B.A., Versluis, M.J., Hoogduin, J.M., Norris, D.G., 2006. BOLD contrast sensitivity enhancement and artifact reduction with multiecho EPI: parallel-acquired inhomogeneity-desensitized fMRI. Magn. Reson. Med. 55 (6), 1227–1235.
Prior, A., MacWhinney, B., 2010. A bilingual advantage in task switching. Biling 13 (02), 253–262.
Runnqvist, E., FitzPatrick, I., Strijkers, K., Costa, A., 2012. An appraisal of the bilingual language production system: quantitatively or qualitatively different from Monolinguals?, In: Bhatia, T.K., Ritchie, W.C. (Eds.), The Handbook of Bilingualism and Multilingualism, second edition. Wiley-Blackwell, pp. 244–265.
Schwieter, J.W., 2013. Lexical inhibition in trilingual speakers. In: Tirkkonen, J., Anttikoski, E. (Eds.), Proceedings of The 24th Conference of Scandinavian Linguistics. Publications of the University of Eastern Finland: Reports and Studies in Education, Humanities, and Theology. University of Eastern Finland Press, Joensuu, Finland, pp. 249–260.
Schwieter, J.W., Sunderman, G., 2011. Inhibitory control processes and lexical access in trilingual speech production. Ling. Approaches Biling. 1 (4), 391–412.
Torta, D.M., Cauda, F., 2011. Different functions in the cingulate cortex, a meta-analytic connectivity modeling study. Neuroimage 56 (4), 2157–2172.
Van den Wildenberg, W.P., Wylie, S.A., Forstmann, B.U., Burle, B., Hasbroucq, T., Ridderinkhof, K.R., 2010. To head or to heed? Beyond the surface of selective action inhibition: a review. Front. Hum. Neurosci. 4.
Verbruggen, F., Logan, G.D., Stevens, M.A., 2008. STOP-IT: Windows executable software for the stop-signal paradigm. Behav. Res. Methods 40 (2), 479–483.
Verhoef, K., Roelofs, A., Chwilla, D., 2009. Role of inhibition in language switching: evidence from event-related brain potentials in overt picture naming. Cognition 110, 84–99.
Wang, Y., Xue, G., Chen, C., Xue, F., Dong, Q., 2007. Neural bases of asymmetric language switching in second-language learners: an ER-fMRI study. Neuroimage 35, 862–870.
Weissberger, G.H., Wierenga, C.E., Bondi, M.W., Gollan, T.H., 2012. Partially overlapping mechanisms of language and task control in young and older bilinguals. Psychol. Aging 27 (4), 959–975.
Woolgar, A., Thompson, R., Bor, D., Duncan, J., 2011. Multi-voxel coding of stimuli, rules, and responses in human frontoparietal cortex. Neuroimage 56 (2), 744–752.
Xue, G., Aron, A.R., Poldrack, R.A., 2008. Common neural substrates for inhibition of spoken and manual responses. Cereb. Cortex 18, 1923–1932.