Bilingual Language Control: Separating Preparation and Production in a Morpho-Syntactic Rule Task.

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Abstract

The role of reparatory process in bilingual language control has been largely overlooked, as traditional language switching paradigms don't separate cued preparation from production. The current study employed a novel paradigm, Rapid Instructed Task Learning (RITL), in which preparatory and production processes of bilingual language control were separately investigated. Results showed that preparatory processes elicited activation in the anterior cingulate cortex (ACC) as well as regions involved in the default mode network (medial prefrontal cortex, posterior cingulate/precuneus, and lateral parietal cortex). Bilateral caudate nuclei were involved in maintaining target language features over the three phases of the RITL. The presupplementary motor area, dorsolateral prefrontal cortex, and left inferior frontal gyrus were most active when the target language was in use during task execution. The results highlight the fact that bilingual language control mechanisms are differentially deployed across time, suggesting multiple dissociable networks.

Introduction

Bilingual language control refers to the set of cognitive abilities that allow a bilingual individual to select and maintain a target language in the face of competing symbolic representations and linguistic rules. (Costa, Miozzo, & Caramazza, 1999; Hatzidaki, Branigan, & Pickering, 2011). The cognitive processes underlying bilingual language control are composed of dissociable processes, namely, selecting which language to use, setting up a linguistic goal, and achieving the goal by using a target language. Bilingual language control allows one to monitor language conflicts between two languages and to guide as well as allocate attention to process the target language. As a result of this mental program, language selection adaptively varies at any given moment depending on contextual cues. In addition, linguistic tasks such as deciding which of multiple competing lexcio-semantic representations to use and which of multiple competing morpho-syntactic rules to execute are processed according to a target language goal. Although these processes may be dissociable, bilingual language control has been viewed as a unitary system in the literature. As such, the functions of bilingual language control regions have not been fully understood. Investigating the neurocognitive nature of bilingual language control mechanism is crucial. In the last decade, whether bilingual language control shapes the brain and mind differentially has been controversial. The advancement of knowledge on how bilingual language control operates will provide some answers to this controversy.

A recent quantitative meta-analysis reported nine brain regions that are reliably involved in bilingual language control (Luk, Green, Abutalebi & Grady, 2011). These results included regions typically associated more generally with cognitive control: the anterior cingulate cortex (ACC), presupplementary motor areas (Pre-SMA), the right precentral gyrus, the dorsolateral prefrontal cortex (DLPFC) and bilateral caudate nuclei. They also included regions more typically associated with language processes such as the left inferior frontal gyrus (BA 44, 47) and the left middle temporal gyrus. Despite a general consensus in the field that these regions participate in bilingual language control, a few limitations, discussed herein, prevent a complete understanding of "how" and "when" these regions contribute to bilingual language control.

First, the bilingual language control literature overlooks and therefore has a limited understanding of the role of preparatory processes. Preparatory processes, in general, refer to a set of dynamic configurations in anticipating the demands of an upcoming task and have been determined to be a crucial part of cognitive control (Dreisbach, & Haider, 2006; Altmann, 2004; Meiran, Chorev, & Sapir 2000; Sohn & Carlson, 2000). During the preparatory processes, mental programs are initiated which allow proactive adjustment to the task at hand (Ruge, Jamadar, Zimmermann, Karayanidis, 2013). The mental programs are then ready to implement task-specific variables. In the situation of multiple stimuli competing for selection, when a target is prioritized based on a cue, preparatory processes prepare for executing the task (Ruge, & Braver, 2007; Monsell, 2003). Likewise, during the preparatory processes of bilingual language control, bilingual individuals prioritize a target language based on language cues and prepare to execute the linguistic task. (Kroll, Bobb, Misra, & Guo, 2008; Hermans, 2000). In line with general cognitive control findings, Reverberi et al. (2015) observed two distinct neural networks of language control in bilinguals. The first network was activated during the phase of "forming an intention" to use a language (i.e., preparatory process) prior to language execution. Motor-related regions were most active during this phase. The second network, which is involved in production, included canonical bilingual language control regions. These findings imply that preparatory and production rely on two dissociable neural networks. However, little is known about the neural substrates of preparatory processes in natural settings of a bilingual's language control.

In the Reverberi et al. (2015) study (and others), the abovementioned language control regions were localized by employing language-switching paradigms such as picture naming and translation tasks (Abutalebi et al., 2008; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Lehtonen et al., 2005; Garbin et al., 2011; Hernandez, 2009). Language switching assumes that a form of higher level language control is featured during that moment when a conflict between two languages is maximized. However, in the traditional language switching paradigm, conflation of preparatory processes and production in a target language leads to an oversight of the role of preparatory processes. For instance, when bilingual participants are asked to name an object or translate a word in the cued language, the language cue and target stimuli are presented at the same time. The absence of temporal separation leads one to miss the crucial information of how language control regions are initially recruited and activated in the preparatory processes.

A second limitation is the fact that bilingual language control has been studied primarily within the domain of lexico-semantic processing, neglecting other levels of language processing including morpho-syntactic processing. To our knowledge, none of the switching paradigms has focused on morpho-syntactic processing. Therefore, we herein attempt to adopt a new paradigm that allows us to decompose language control and investigate bilingual morpho-syntactic processing. Considerable research has demonstrated that when a lexico-semantic item from one language is accessed, the item's relevant information from the other language is activated in parallel. (Guttentag, Haith, Goodman, & Hauch, 1984; Costa, Caramazza, & Sebastian-Galles, 2000; Hermans, Bongaerts, De Bot, Schreuder, 1998; Rodriguez-Fornells et al., 2005). This cross-linguistic interference is not constrained at only the lexico-semantic level (Hatzidaki, Branigan, & Pickering, 2011). The support for co-activation at all levels is the fact that a lexico-semantic item itself contains different morpho-syntactic properties (e.g., number, and gender) (Hatzidaki, Branigan, & Pickering, 2011). Intersentential code switching and cross structural priming is more evidence that cross-linguistic interference is not limited to lexico-semantic processing (Hatzidaki, Branigan, & Pickering, 2011; Pickering, & Ferreira, 2008). Due to the cross-linguistic interference in morpho-syntactic processing, extra demands are placed in bilinguals to use the appropriate grammar set between the two languages. For instance, to achieve the desired linguistic goal of pluralizing a noun, an Italian-English bilingual must activate two grammatical (i.e., morpho-syntactic) rules: adding an -s or i/e. These rules are represented and controlled in the neural systems and compete for selection contingent on the target language (Buchweitz, & Prat, 2013). A recent study by Stocco and Prat (2014) observed that using two languages flexibly develops brain circuitry that computes domain-general rule selection and execution differently. Considering the findings that both non-linguistic and linguistic rule-based behaviors are executed through employing highly overlapping regions of the prefrontal cortex (Patel, 2003; Tettamanti et al., 2009; Baldo, & Dronkers, 2007), the extra demands placed in bilinguals' morpho-syntactic process may train the brain circuit involved in non-linguistic rule-based behaviors. In order to gain a new perspective on bilingual language control, a model that addresses how the known neural networks of bilingual language control support morpho-syntactic processing is necessary. Of particular interest to this paper, a new approach was taken which allows investigation of bilinguals' morpho-syntactic representation and control that are not modulated by lexico-semantic processing.

A third limitation is that with the traditional switching paradigms, it is difficult to determine to what extent these bilingual language control regions are general cognitive control regions or specific to linguistic processes per se. In the switching paradigm, the language cue that instructs the brain which language to use is often found in a linguistic form that directly elicits task-relevant activation. For instance, an auditory cue for a Spanish-English switching task, is either ‘say’ or ‘diga’ (‘say’ in Spanish). A visual cue for Chinese-English switching task is either a Chinese character ‘读’ or an English alphabet letter counterpart ‘read’, which points to which language is in use. The linguistic form of the preparatory cues induces difficulty in determining the stimulus and response mapping on which neural responses are purely drawn from activation of language control or from linguistic task processing.

The current paper addresses these three limitations with the development of a novel paradigm that allows:1) the separation of preparatory processes from production, 2) the investigation of bilinguals’ morpho-syntactic representation and control structures, and 3) the separate investigation of control structures from bottom-up linguistic influences. The Rapid Instructed Task Learning (RITL) paradigm recently gained popularity in investigating a major cognitive architecture: how the human brain performs novel tasks following rule-based instructions (Stocco, & Prat, 2014; Stocco et al., 2012; Cole, Laurent, & Stocco, 2013). The RITL paradigm reflects a mental program where instructions are used to activate, guide, and elicit a target response to resolve conflicts between competing responses. Therefore, encoding an instruction and executing a task phase are performed independently in the RITL paradigm, which allows isolation of the neural computations associated with the mental program and implementation of the specific variables. During the encoding phases, a cue is presented to instruct a desired task (e.g., adding) prior to a target stimulus (e.g., number). Subsequently, the stimulus, the specific variable that binds into the mental program, is given in the next execution phase (Stocco, & Prat, 2014; Stocco et al., 2012; Cole, Laurent, & Stocco, 2013). This separation allows one to address a representation of control mechanism(s) that is established to perform a task without influence of the stimulus.

The aim of this study is to examine separately preparatory processes and production in the context of a morpho-syntactic task. We hypothesize that the nine bilingual language control regions will differentially participate in the three phases of language control. Specifically, some of the regions will process crucial information on language control such as language selection. Others will keep track of the target language information while still others will be involved in sub-levels of language interference, such as controlling lexico-semantic and morpho-syntactic interference in bilinguals during the production. We will also explore how bilinguals' morpho-syntactic information is represented and controlled in the bilingual brain.

Materials and Methods

Participants

Twenty-four, right-handed Spanish-English bilinguals (20 females; aged 18-31) participated in the present study. All participants were recruited through University of Washington. They were highly proficient in both languages, and acquired their second language no later than the age of 7. All participants gave signed informed consent, which was approved by the University of Washington Institutional Review Board. All individuals reported no history of neurological disorders. Each participant was compensated for the participation.

Data from one of the participants was discarded due to excessive motion which is defined as having more than ten percent of image volumes with greater than 1 millimeter (mm) of peak to peak motion.

Stimuli

In the Rapid Instructed Task Learning paradigm, participants executed different tasks based on specific instructions for each trial. Instructions included information about target language and linguistic rules. The target language was either English or Spanish, and the linguistic rule was either a single rule or a combination of single rules. The single rules were either noun-related or verb-related, and the combination of these two rules was designed to add a level of complexity in computation as noun and verb conjugations were required. The instructions were coded using abstract symbols. A pound sign (#) referred to English, and an asterisk (*) referred to Spanish. Linguistic rules were coded as 1, 2, and A, B. The 1 and 2 were noun-related rules whereas A and B were verb-related (See details in ***Table 1***).

Insert Table 1 About here

Experimental Design

As in the original Rapid Instructed Task Learning (RITL) paradigm, each trial was composed of three phases (Stocco et al.,2012; Cole, Laurent, & Stocco 2013) (See Figure 1). (a) *Encoding* phase, in which the target language and rule(s) was presented consecutively with a jitter in between; (b) *Execution* phase, in which a word variable(s) was presented; and (c) *Response* phase, in which participants responded whether the answer shown on the screen was the correct outcome of the given operations of the target language and rule(s).

Participants were instructed to press a button upon encoding instructions and executing them. Both encoding and execution phases were self-paced with a time limit of 8000 milliseconds (ms) after which the trial proceeded to the jitter phase. The time limit for the

Response phases was set at a much shorter 2000 ms to encourage the participants to complete the operations during the Execution phase and not during the Response phase. Encoding target language, encoding rule(s), execution and response phases were divided by temporal jitters, the duration of which varied randomly between 500 and 11500 ms. The jitters reduced the collinearity between the phases and allowed for better estimation of the corresponding brain activity (Dale, 1999).

There were two versions of RITL in which the symbols used for Spanish and English were counterbalanced across participants. The words used in each version were normed based on their frequency of usage in English (mean occurrence = 168.52 as defined by Kucera and Francis, 1967, frequency norms). Half of the words were translated into Spanish for version A and the other half were translated into Spanish for version B. Hence, each word occurred in both languages across participants. Response hand for “yes” and “no” was also counterbalanced across participants.

The LITL paradigm consisted of seventy-two trials divided into 3 runs of 24 trials each. Each run consisted of a set of 12 English and 12 Spanish trials. The set for each language was broken down into 4 noun, 4 verb, and 4 combinations of noun and verb trials.

Insert Figure 1 About here

Materials

Paper and pencil tasks.

Handedness inventory. The Oldfield Handedness Inventory (Oldfield, 1971) measures handedness of the participants.

English grammatical proficiency test. The English grammatical Proficiency test is a subtest of the "Examination for the Certificate of Proficiency in English" developed at the University of Michigan. It involves 20 multiple-choice questions that assess grammatical proficiency. Completion of the test takes approximately 5 to 10 minutes (English Language Institute, 2006).

Spanish grammatical proficiency test. The Spanish Grammatical Proficiency is a subtest of the standardized Spanish grammar proficiency test issued from the Ministry of Spanish Education for diplomas in Spanish as a foreign language (el Ministerio de Educación, 1988).

Nelson and Denny reading test. The Nelson and Denny Reading Test (Brown, Fishco, & Hanna, 1993) is a timed, multiple-choice test of vocabulary that is normed through the college level. This test takes approximately 15 minutes.

Computerized tasks.

Language experience and proficiency questionnaire. A modified version of Marian, Blumenfeld, & Kaushanskaya (2007) et al.'s Language Experience and Proficiency Questionnaire is a questionnaire designed to assess language experience and proficiency.

Bilingual switching questionnaire. A modified version of Rodriquez-Fornells, Krämer, Lorenzo-Seva, Festman, & Munte (2012) et al.'s Bilingual Switching Questionnaire is a self-reported assessment of bilingual language use and includes questions investigating switching tendencies between languages. The modified version includes an assessment of intentionality with switch questions such as "When speaking in English, how often do you accidently switch to Spanish?" This survey takes approximately 5 minutes.

Motivation checklist. Motivation Checklist includes 16 debriefing questions that are used to evaluate how the participant views all the tasks performed and their overall difficulties.

Experimental Procedure

Behavioral Testing

Behavioral testing was composed of a battery of individual difference measures, which included a language experience and proficiency questionnaire (Marian, Blumenfeld, & Kaushanskaya, 2007), an English grammatical proficiency test, the modified Spanish grammatical proficiency test, the vocabulary portion of the Nelson-Denny reading test (Brown, Fishco, & Hanna, 1993), the Edinburgh Handedness Inventory (Oldfield, 1971), and the modified Bilingual Switching Questionnaire (Rodriguez-Fornells, Krämer, Lorezo-Seva, Festman, & Munte, 2012).

Practice

The practice session was composed of a memory task and a practice version of Rapid Instrucated Task Learning (RITL) Task. The memory task was administered to help participants acquire the meaning of codes that were used in the RITL paradigm. Each of the code and rule pairs was shown three times in a random order and participants were asked to type the corresponding code if a rule was given or to type a rule if a code was given. In order to complete the memory task, the participants had to reach a criterion of accurately answering the same question at least two times. After the memory task, they underwent 16 RITL practice trials. In the practice trials, participants were given explicit instructions and feedback on their accuracy rate and response time to help them perform accurately in the actual trials.

fMRI imaging session

We adopted an event-related design in order to collect optimized blood oxygenation level dependent responses. Fixations that varied in durations as a function of the characteristics of each trial were applied between phases to adjust hemodynamic responses after the duration of each fixation had been determined after a few pilot studies.

Image Acquisition

The data were collected using a Philips 3.0 T Scanner at the Integrated Brain Imaging Center at University of Washington. The study was performed with a gradient echo planar pulse sequence with TR = 1000ms, TE = 30ms, and a 60 flip angle. Sixteen oblique axial slices were imaged with an interleaved acquisition, and each slice was 5mm thick with a gap of 1 mm between slices. The resulting acquisition matrix of 64 x 64 with 3.125 x 3.125 x 5 mm voxels covered the majority of the brain with the exception of the most anterior portion of the temporal lobe, the most anterior portion of the orbital frontal lobe, and the inferior portion of the cerebellum with some variation across participants.

Statistical Analysis

The present investigation will first employ voxel-wise estimation by the phase itself: Encoding Target Language, Encoding Rule and Execution phases to functionally dissociate the language control which will eventually reveal the nature of each phase. Afterwards, the voxel-wise estimation will be compared to the behavioral measurement, reaction time, to learn the behavioral cost of eliciting such neural response in each phase. Lastly, the region of interest analysis will be carried out in the nine language control regions to determine whether language control regions are differentially involved by phases: Encoding Target Language, Encoding Rule and Execution and/or Language Type: English and Spanish.

Predefined Volumes of Regions of Interest (ROI)

Luk, Green, Abutalebi and Grady (2011) conducted meta-analysis on cognitive control in bilinguals, and some consensus is being made by identifying the seven brain regions that are associated with bilingual language control: presupplementary motor areas (Pre-SMA), the right precentral gyrus, the left inferior frontal gyrus (BA 44, BA 47), the left middle temporal gyrus, dorsolateral prefrontal cortex (DLPFC) and the right caudates. The seven Talairach coordinates were transferred to MNI coordinates using Ginger ALE 2.3.3 for further analysis. In addition to the seven regions, the left caudate and the anterior cingulate cortex (ACC) were added. Luk, Green, Abutalebi and Grady (2011) stated that both regions have been associated with not only bilingual language control but also general cognitive control. Due to the traditional subtraction methods between bilingual language control and general cognitive control baseline tasks, their activations were not observed in their meta-analysis. Therefore, the left caudate and ACC were included in the current investigation.

Insert Table 2 About here

Results

Behavioral Results. Accuracy rates were high across participants (M = 87.62 %, SD = 9.03). Response times were analyzed using a one-way analysis of variance (ANOVA) between three task phases: Encoding Target Language (TL), Encoding Linguistic Rule (RL), and Execution. A main effect of task phase was revealed (F (2,66) = 23.72, MSE = 13383924.35) and post-hoc multiple comparison analyses showed that response times for Encoding TL were significantly shorter than either for Encoding RL (*M* = 2500.86 (msec)) or for Execution *(M* = 2634.89 (msec)). Mean response times in the three task conditions are depicted in ***Table 3***.

Insert Table 3 About here

Distribution of Activation by Task Phase. General linear model estimates of activation during the Encoding TL, Encoding RL, and Execution phases are described in the subsequent sections (***Table 4***).

Encoding Target Language. The voxel-wise analysis revealed that preparing to use a TL recruited a largely distributed network with peak activation in the medial frontal gyrus, extending broadly into the canonical left hemisphere (LH) language regions (e.g., inferior frontal gyrus and posterior superior temporal gyrus), their right hemisphere (RH) homologues, bilateral prefrontal and parietal cortices, and subcortical regions including the basal ganglia. It is interesting to note that all of the regions previously associated with bilingual language control became activated during this phase of the task, in which no linguistic information was presented (See ***Figure 2***).

Encoding Linguistic Rule. Encoding RL recruited a more focal and left-lateralized pattern of activation than did preparing to use a TL. Specifically, the peak activation was centered around the left cingulate cortex, extending laterally into the left inferior frontal cortex and medially into the basal ganglia. Bilateral parietal activation was also observed (See ***Figure 2***).

Execution. Our results indicated that activation during rule execution was highest over left inferior frontal regions, but also included bilateral parietal and prefrontal cortices as well as the basal ganglia. This network included all of the regions active during linguistic rule preparation, as well as a subset of regions activated during target language preparation (See ***Figure 2***).

Insert Figure 2 and Table 4 About here

Region of Interest (ROI) Analysis by Task Phase

Follow-up ROI analysis revealed a main effect of task phase (Encoding Target Language, Encoding Linguistic Rule, and Execution) on 6 regions out of 9 regions of interest (i.e., anterior cingulate cortex, left inferior frontal gyrus (BA 47), left middle frontal gyrus, left inferior frontal gyrus (BA 44), right precentral gyrus, and midline pre-SMA). Among the 6 regions in which the main effect of task phases was found, the results were reanalyzed using post hoc multiple comparison analysis. With this follow-up analysis, 3 functional sub-networks were identified based on the patterns of activation across three tasks. One group of regions responded more strongly when cued about target language than when preparing a rule or executing the task. While there was no significant difference in activation of the right precentral gyrus between the Encoding TL and Encoding RL phases, there was a significant difference between the Encoding TL and Execution phases. The anterior cingulate in particular showed higher activation in Encoding TL than in either Encoding RL or Execution phases (See ***Figure 3***).

Insert Figure 3 About here

Another group of brain regions notably showed increased activation as a participant moved forward through the three phases. The Pre-SMA showed significantly different activation between Encoding TL and Execution. The left middle frontal gyrus (dorsolateral prefrontal cortex, BA 46), left inferior frontal gyrus (Broca areas, BA 47), and insula (BA 47) were mostly involved in implementing target language and linguistic rules. These three regions showed higher activation in Execution than either in Encoding TL or Encoding RL phases (See ***Figure 4***).

Insert Figure 4 About here

The last pattern of the sub-network includes right caudate and left middle temporal gyrus (BA 37). These bilateral caudate and left temporal gyrus (BA 37) regions are equally involved in Encoding TL, Encoding RL and Execution, tracking the variables as indexed by target language and linguistic rules (See ***Figure 5****)*.

Insert Figure 5 About here

Discussion

The Importance of Preparatory Processes in Language Control

The hypothesis in this study was that individual bilingual language control regions may carry out dissociable sub-functions within bilingual language control. With the goal of identifying regions that engage differentially during the preparation and production phases of bilingual language control, the present experiment separated bilingual language control into the phases of preparation, encoding linguistic rules and production in the context of a morpho-syntactic task.

Different patterns of behavior and neural responses across the three phases of the RITL task support the hypothesis. In the preparation phase, the reaction times of participants were faster than in the other two phases, implying that the task of planning which language to use may involve a rapid selection. Although this process is rapid, it requires engagement of multiple cortical areas: a whole brain analysis showed widespread bilateral activation during this preparation phase, which included the nine individual bilingual language control regions as well as language relevant regions.

These observations reveal that preparatory processes in bilingual language control elicit significant neural activity. The role of preparatory processes has been overlooked in the previous literature. Traditionally, experimental paradigms in the neuroimaging literature have reflected the notion that bilingual language control operates *on the fly*. For instance, in Hernandez et al., the subjects were cued to select the target language by being given a word in that language and were asked to immediately naming a picture in that language (Hernandez, Martinez, & Kohnert, 2000). Similarly, in translating tasks (e.g. Price, Green, & Von Studnitz, 1999), preparatory and production phases were not separated. Thus, findings from traditional experimental designs examining bilingualism have not been able to reliably isolate the preparatory stage of bilingual language control mechanisms due to a lack of temporal separation between language selection and production in the experimental designs.

The Time Courses for Preparation, Retention, and Production in Bilingual Language Control

To our knowledge, we are the first to attempt to observe the time courses of neural activities in the nine regions of language control. The results from a region of interest analysis (ROI) over the three phases support our hypothesis that language control may be functionally dissociable. The nine canonical bilingual language control regions were involved in bilingual language control in three different ways. The dorsal anterior cingulate cortex (dACC) and the right precentral gyrus were primarily involved in preparing to use a language. The middle temporal gyrus and bilateral caudates, on the other hand, were involved in retaining the usage of a target language. Finally, the sub-areas of the left inferior frontal cortex (BA 44, 47) and dorsolateral prefrontal cortex (DLPFC, BA 46) were mostly involved in producing the language.

ACC as the Core Region of Preparatory Processes in Bilingual Language Control

Among the bilingual language control regions that play unique roles in language control, the ACC was found to be involved in preparatory processes. Traditionally, it has been proposed that the ACC is a part of domain-general cognitive control circuitry (Botvinick et al. 1999). Specifically, the ACC engagement was reliably observed in tasks involved in monitoring cognitive conflicts such as overriding prepotent response and selecting a target among competing inputs (Barber & Carter 2005, Carter, Botvinick, & Cohen, 1999; Botvinick et al. 2004; Carter et al., 1998; Badgaiyan, & Posner, 1998; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). In a similar vein, in bilingual language control, ACC activity has been associated with monitoring ‘language’ conflict (Abutalebi et al., 2012; Abutalebi et al., 2008). Language conflict has been operationalized as language switching in traditional bilingual language control studies and ACC activity was consistently observed during the language switching tasks. Language conflict arises because two languages are competing for response selection, and switching requires overriding the current language in use (De Groot, Delmaar, & Lupker, 2000; Van

Heuven, Schriefers, Dijkstra, & Hagoort, 2008; Van Heuven, Dijkstra, & Grainger, 1998). However, it is not certain whether or not the ACC engages only during the language switching phase. As an example, Abutalebi et al. (2008) reported that the ACC activation was observed in bilingual language contexts irrespective of whether the language of the trial was switched or repeated. In dual language blocks of trials where two languages were involved, there were both repeated and switched language trials. The single language block used only one language. ebi et al. (2008) found that bilingual participants used neural resources from the ACC in repeated language trials in the dual language block but not in repeated trials in the single language block. This finding suggests that the ACC activates when participants are consciously aware of the presence of two languages. Furthermore, the ACC engagement is not constrained to language switching but includes monitoring language conflict in a bilingual context.

Similarly, the new findings reported here suggest that the function of the dorsal part of the ACC also extends beyond language switching. The dorsal ACC (dACC) showed transient increases in preparatory phases whether a language was repeatedly used or switched from the previous trial. The dACC activity was elevated during the preparatory processes but dropped significantly once the target language was selected (See ***Figure 11***). This suggests that dACC activation is responsive particularly to the preparatory process of bilingual language processes. However, it is not sensitive to whether a target language is switched or repeatedly used. These findings are in line with the Luks, Simpson, Feiwell, & Miller (2002) report in general cognitive literature which pointed out that the ACC is not constrained to conflict monitoring from switching tasks but also in the preparatory phases, regardless of whether preparatory cues informed the participants to switch or repeat the previous task.

We can further infer that the ACC involves global levels of language control rather than sub-levels of control based on the fact that morpho-syntactic and lexico-semantic interference (which appear in the sub-levels) are absent in the preparatory phase. It is important to make this distinction, as divergent neurocognitive demands have been confirmed with differential neural activities in the preparatory and production phases of our study. Global control engages an entire language set while local control involves sub-levels of language processing (Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2015; Guo, Liu, Misra, & Kroll, 2011). Although both levels of control are required in bilingual language control, they have different time courses of activation. When receiving language cues that indicate which of two languages to use in a given situation, language selection occurs by evaluating the two language systems. In contrast, during language production, language is evaluated in sub-levels. The existence of global levels of bilingual language control has been shown in the studies on roles of language cues. If language cues detected during the preparatory processes were mismatched with the language in production, bilingual participants showed delayed latency to use the incongruent language or decreased proficiency of decreased (Woumans et al., 2015; Zhang, Morris, Cheng and Yap, 2013). These findings demonstrate that a target language is selected before language is in use. We suggest that the ACC is involved in the global levels of bilingual language control in the earlier preparatory processes in bilingual language control.

Sensitivity of Target Language Feature in Bilateral Caudate Nuclei

We observed that the bilateral caudate nuclei were equally active in each of the three phases: preparing to use the target language, encoding, and executing rules. Based on these findings, we propose that the bilateral caudates keep track of the target language features.

Crinion et al. (2006) added vital evidence that language monitoring in bilinguals is accomplished through the left caudate. Utilizing the priming effect that is reflected as neuronal adaptation, Crinion et al. (2006) demonstrated that, specifically, the left caudate is sensitive to language changes in bilingual language processing. When semantically-related words were presented sequentially, reduced neural activation was observed in all related regions of the brain during the processing of the second word in the pair due to neuronal adaptation (e.g., English trout - SALMON or German: forelle- LACHS). Neural adaption was found to be maintained across languages so long as the words were semantically related. However, when the semantically-related words were presented in different languages (e.g., trout - LACHS), reduced activation was observed in all regions except for the left caudate. Crinion et al. (2006) reasons that the absence of the neural adaptation effect in the left caudate arises from its language sensitivity. The unchanged activation level in the left caudate may result from its monitoring of which language is in use.

The data from the present study supports the theory that the caudate nuclei are involved in monitoring the target language features in bilingual language processing. Equal amounts of activation in bilateral caudate were observed in the three phases in which the target language was required. In the Encoding TL phase, target language features were introduced. In the Encoding RL phase, the target language features were used to retrieve language-specific rules. In the Execution phase, target language features were used to manipulate the given lexical items with morpho-syntactic rules. Because the language in use was constant, and because the bilateral caudates were activated equally throughout the phases, it can be inferred that the bilateral caudates are involved in keeping track of the features of that target language. These findings are consistent with previous bilingual literature that states that the bilateral caudates are sensitive to a target language in bilingual language control.

Involvement of Frontal Cortex in Bilingual Language

Of the nine generally accepted regions of bilingual language control, six were in the prefrontal cortex. Of those six regions, four were more activated during language execution. The findings of this study provide a more detailed account of how the six parts of the frontal cortex are involved in bilingual language control. As discussed earlier, the ACC and the right precentral gyrus form the preparatory network. The four remaining regions, the presupplementary motor area (Pre-SMA) (BA 6), dorsal lateral prefrontal gyrus (DLPFC) (BA 46), and the two sub-regions of inferior frontal gyrus, pars opercularis (BA 44) and pars triangularis (BA 47), were more activated in production than in preparatory and encoding rule phases.

Based on the findings, it can be proposed that the Pre-SMA, DLPFC, and inferior frontal gyrus are involved in adjusting local levels of language interference when language is in use. Language interference occurs because, despite a target language being chosen during the preparatory processes, local levels such as lexico-semantic items and morpho-syntactic rules are still accessible. Code switching is an example of local level interference during production. Even though the target language is chosen during the preparatory process, bilingual individuals are still able to use the non-target language's lexico-semantic items or morpho-syntactic rules during production (Costa, Caramazza, & Sebastian-Galles, 2000; De Groot, Delmaar, & Lupker, 2000; Pickering, & Ferreira, 2008; Hatzidaki, Branigan, & Pickering, 2011). Because Pre-SMA, DLPFC, and inferior frontal gyrus are more active during the production phase, it can be inferred that they are involved in local level control.

Particularly, during the execution phase, the local level of language control is operated as shown by the activation of pars opercularis and pars triangularis (the two sub-regions of the inferior frontal gyrus). The pars opercularis is related to syntactic processing and pars triangularis is related to increased demands in semantic processes and thematic role assignment (Newman, Just, Keller, Roth, & Carpenter, 2003). This supports the claim that the activated regions in production are differentially involved in local levels of language control involving lexico-semantic and morpho-syntactic processing.

Alternatively, the pattern of increased activation in Pre-SMA, DLPFC, and inferior frontal gyrus may be reflective of an increased working memory load. The DLPFC has been robustly associated with working memory in task switching including language switching task (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001). In the current study, language switching was not implemented. However, as a bilingual participant progressed, the paradigm presented increasingly more information for the participant to maintain and later utilize. Thus, the gradual increased activity in the areas might be reflective of the increased amount of working memory that is required in the RITL paradigm.

Conclusion

The results of the current study, which employed a novel paradigm to study bilingual language control across time, suggest that such language control is not executed by a unitary system. Rather, we describe dissociable mechanisms that are deployed across various phases and levels of bilingual language control.

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Tables

Table 1. *Sample Stimuli for Spanish and English Trials with Sample Experimental Codes in Parentheses*

	English (#)		Spanish (*)	
Rule	Stimulus	Response	Stimulus	Response
Pronoun (1)	UNCLE	HE	TIÓ	EL
Plural (2)	UNCLE	UNCLES	TIÓ	TIÓS
Past (A)	WALK	WALKED	CAMINAR	CAMINARON
Future (B)	WALK	WILL WALK	CAMINAR	CAMINARA
Combination (1A)	UNCLE WALK	HE WALKED	TIÓ CAMINAR	EL CAMINARON

Table 2. *Description of Regions of Interest (ROIs) Used for Neuroimaging Analysis.*

Region	Brodmann's Area	Radius (mm)	Centroid MNI coordinates		
			x	y	z
From Luk et al. (2011)					
Left DLPFC	46	8	-44	13	29
Left Inferior Frontal	44	8	-48	15	11
Left Lateral Orbitofrontal	47	8	-31	18	-2
Left Middle Temporal	37	8	-48	-42	-65
Pre-SMA	6	10	1	1	57
Right Precentral	6	8	40	-9	32
Right Caudate		6	14	5	16
Additional ROIs					
ACC		10	0	32	24
Left Caudate		6	-14	5	16

Table 3. *Behavioral results from RITL in the fMRI scanner. Reaction times (msec) and Standard Error of the Mean (SEM) in Encoding Target Language Encoding Linguistic Rules, and Execution phases are described.*

	Encoding		Execution
	Target Language	Linguistic Rule	
Mean RT (SEM)	1474.57(119.18)	2500.86(143.86)	2634.89(111.76)

able 4. *Centroids, Cluster Descriptions, and Statistics for Patterns of Activation in the Three Task Phases* *ncorrected p = 0.001, k =14).*

				MNI coordinates		
Regions	Peak Brodmann's Area	Cluster Size	Peak T Value	x	y	z
(A) Encoding Target Language						
Bilateral SMA, Anterior/Middle cingulate, Dorsolateral prefrontal	24	58733	10.76	-10	6	52
Left Inferior Parietal	40		9.98	-38	-56	42
Left Basal Ganglia, Insula, Inferior Frontal			9.31	-20	2	18
Left Inferior Parietal	3		9.27	-54	-20	26
Left Precental	4		7.79	-42	-6	24
Left Superior Temporal	39		7.01	-40	-48	12
Left Inferior Occipital	37		6.98	-50	-72	-4
Left Hippocampus			6.88	-30	-30	4
Left Superior/Middle Frontal			8.47	30	30	4
Right Basal Ganglia			8.05	18	6	14
Right Superior Parietal	7		8.03	38	-66	52
Right Precental	6		7.86	44	-6	24
Right Temporal	41		7.81	34	-30	0
Right Inferior Temporal	37		7.64	44	-70	-4
Right Superior/Dorsolateral Frontal	10		6.55	22	56	16
Right Cingulate	23		6.90	2	-34	28
(B) Encoding Rule						

Bilateral SMA, Middle Cingulate, DLPFC, Superior/Medial Frontal,	6	32333	11.39	-6,	4	54
Left Thalamus, Pre/Post Central, Posterior Cingulate, Dorsolateral Prefrontal, Inferior Frontal, Insula, Striatum			9.99	-12	-20	8
Left Inferior Parietal/Supramarginal	40		8.94	-32	-52	42
Left Precentral	4		8.60	-32	2	60
Left Superior Parietal	7		7.61	-12	-74	44
Left Caudate Nucleus			7.58	-6	24	2
Left Insula	13		7.16	-46	6	2
Right Precentral, Caudate Nucleus			8.68	32	-10	28
Right Thalamus			8.20	16	-20	10
Right Medial Globus Pallidus			7.74	14	-4	-2
Right Middle Occipital	18		7.44	30	-94	2
Right Caudate Nucleus			6.43	4	18	8
(C) Execution						
Left Inferior Frontal, Insula, Superior/Middle Frontal, Pre/Postcentral, Putamen, Temporal	44,45	27557	12.77	-42	14	18
Bilateral Supplementary Motor Area, Bilateral Medial Superior, Bilateral Dorsolateral Frontal, Right Anterior/Middle Cingulate, Superior,	6		9.74	-6	6	56

Medial Frontal						
Left Parietal, Middle Occipital	40	931	9.55	-30	-66	48
Left Middle Occipital	18	136	8.00	-24	-96	2
Left Striatum		383	7.62	-20,	-2	2
Left Thalamus		184	7.50	-10	-18	4
Left Precentral	6	56	6.83	-30	0	58
Left Middle Temporal	21	17	6.63	-58	-42	-6
Right Calcarine	18	219	10.10	26	-96	2
Right Striatum		275	7.82	12	2	-2
Right Middle Frontal		140	7.81	38	6	60
Right Insula	13	106	6.84	32	24	0
Right Inferior Parietal	7	194	6.77	32	-56	44

ote. MNI = Montreal Neurological Institute.

Figures

Figure 1. *Schematic of a sample trial from Linguistic Rapid Instructed Task Paradigm, displaying two Encoding phases (i.e., Target Language, Rule), Execution, and Response.*

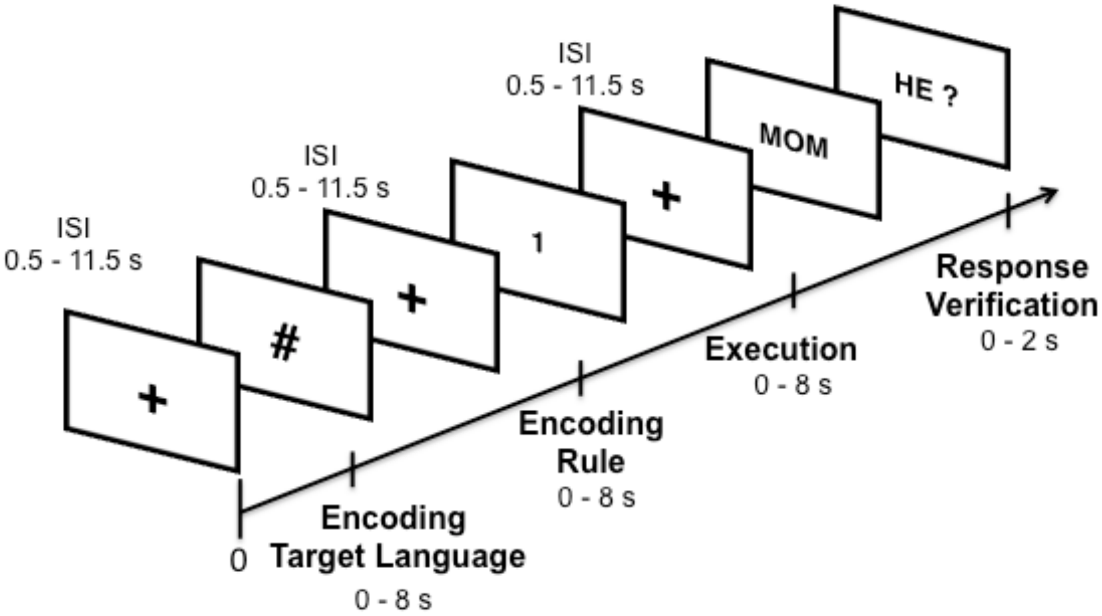

Figure 2. *Statistical maps depicting significant activation patterns across the three task phases (uncorrected p = 0.001, k =14).*

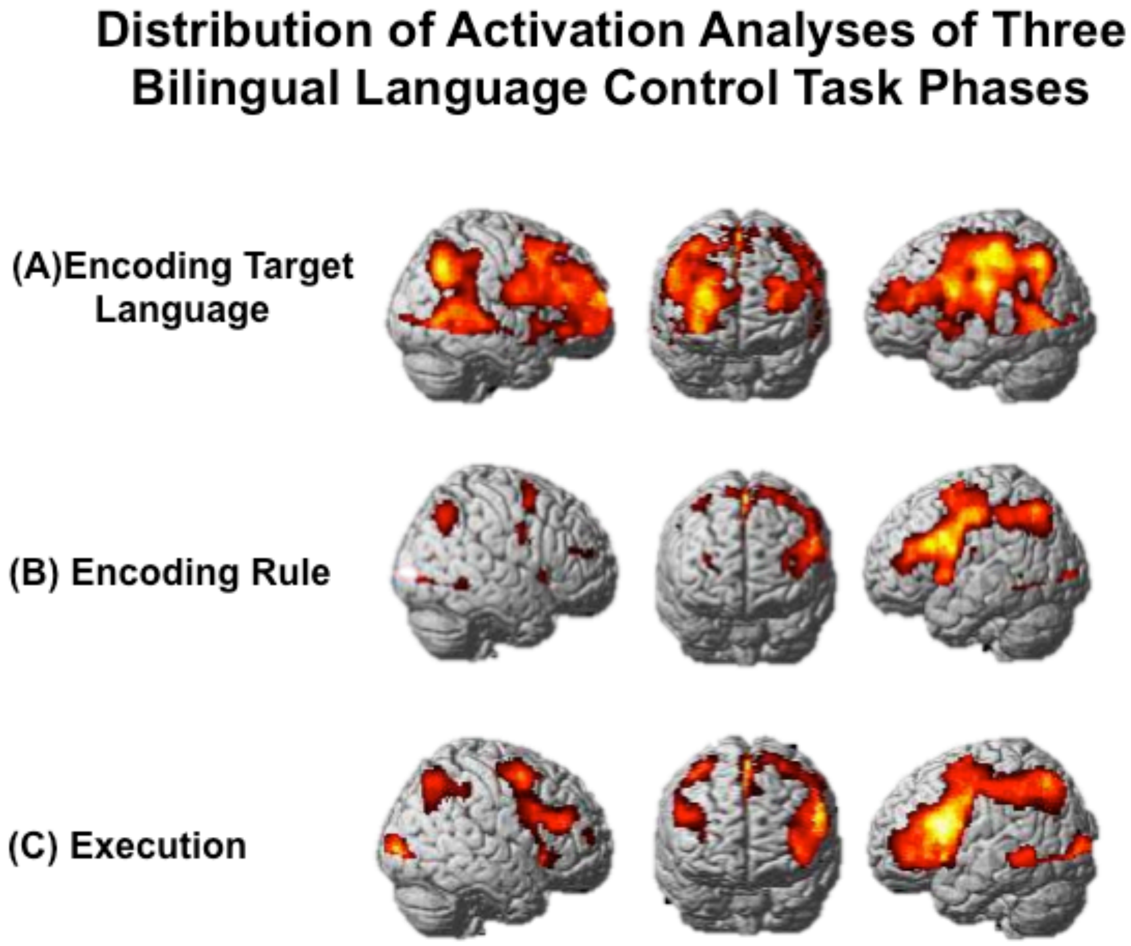

Figure 3. *Mean beta weight extracted in each phase in two regions of interest: anterior cingulate cortex, and right precentral gyrus (BA 6).*

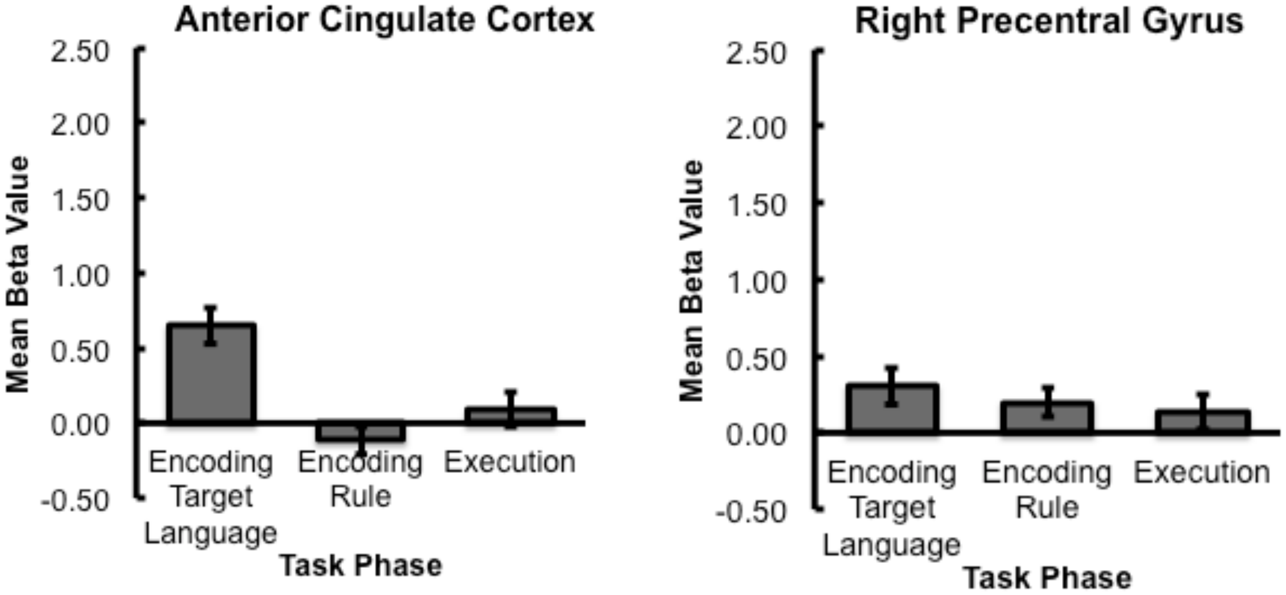

Figure 4. *Mean beta weight extracted in each phase in three regions of interest: midline presupplementary motor area (Midline Pre-SMA), left inferior frontal gyrus (BA 47, 44) and left dorsolateral prefrontal cortex (BA 46)*.

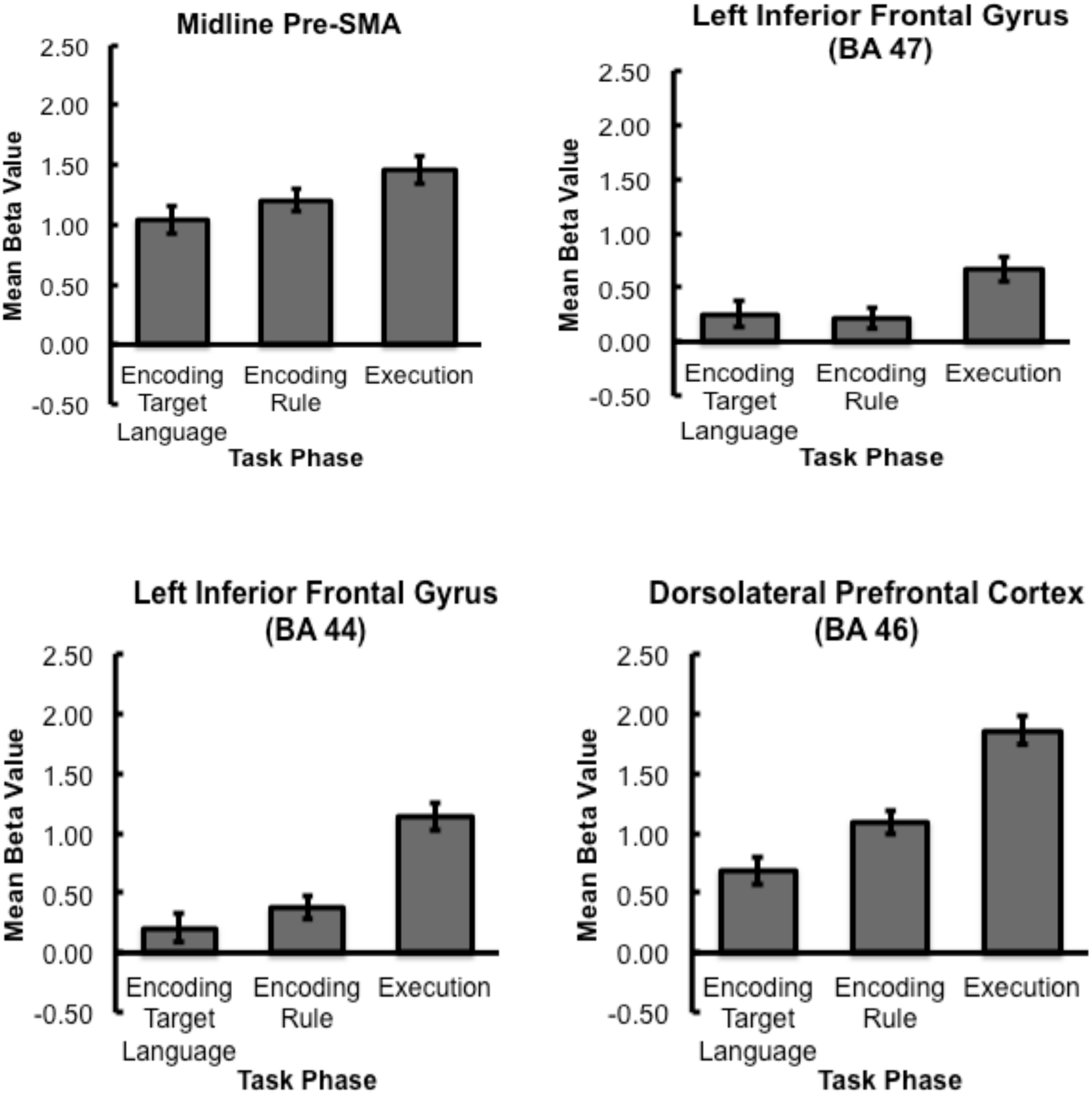

Figure 5. *Mean beta weight extracted in each phase in three regions of interest: left caudate, right caudate, and left middle temporal gyrus (BA 37). Beta weights remained the same in each phase: Encoding Target Language, Encoding Rule, and Execution.*