Global Language Control in Bilingual Language Processing

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Abstract

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The majority of research on language processes has been conducted using monolingual English speakers, although more than fifty percent of current world population is bilingual. As a consequence, our understanding of language is limited, particularly with respect to the types of processes that are unique to bilinguals. Bilingual language processing differs from monolingual language processing in that it requires global language control to resolve a conflict arising from simultaneous activation of two languages. My doctoral dissertation will summarize the results of four studies aimed at understanding the neurocognitive bases of the processes by which bilinguals execute such global language control.

Chapter 1. Introduction

More than fifty percent of the population are bilingual (Shin & Kominsky, 2010), but the majority of research on the neurobiology of language processes has been concentrated on monolingual English speakers (Kovelman, Baker, & Petitto, 2008; Marian & Spivey, 2003; Watson & Bialystok, 1991). As a consequence, our understanding of linguistic processes in the brain are limited, in particular with respect to the facet of language that is unique to bilinguals (Abutalebi & Green 2007; Bialystok & Kroll, 2017; Guo, Misra, & Kroll, 2011). Considerable research on bilingual language processing has shown that both languages are simultaneously co-activated and compete for selection during bilingual language use (Costa, Miozzo, & Caramazza 1999; Hatzidaki, Branigan, & Pickering, 2011; Kroll, Bobb & Wodniecka, 2006; Goldrick, Putnam, Schwarz, 2016). As a result, bilingual language processing demands an additional management mechanism that selects *between* languages. This process, defined by De Groot and Christoffels (2006) as ***global language control***, is the primary focus of my dissertation research. I am particularly interested in the mechanisms by which global language is accomplished, how they compare to ***local language control*** mechanisms shared by monolinguals and bilinguals, and involve the online selection of word forms and application of grammatical rules *within* a target language.

The Adaptive Control Hypothesis (ACH) first proposed by Abutalebi and Green (2007, see also Green & Abutalebi, 2013 for an updated version) is the most comprehensive existing proposal of the neurobiological mechanisms by which bilinguals accomplish language control. According to the ACH, bilingual language control is accomplished through eight candidate "control" processes: goal maintenance, conflict monitoring, interference suppression, salient cue detection, selective response inhibition, task engagement, task disengagement, and opportunistic planning. These sub-component processes are thought to involve neural regions more generally implicated in cognitive control, including: anterior cingulate cortex (ACC), pre-supplementary motor area (pre-SMA), left inferior frontal gyrus (IFG) and dorsolateral prefrontal cortex more broadly defined (DLPFC), parietal cortex, subcortical basal ganglia nuclei (primarily the caudate nucleus), thalamus, right inferior frontal gyrus, and cerebellum. One important focus of the ACH is that the extent to which these processes and candidate mechanisms are deployed varies depending on the language context a bilingual is operating in. However, empirical research describing if and when these regions carry out global and local language control in bilinguals is largely lacking.

One meta-analysis of neuroimaging studies of bilingual language control provided partial support for the ACH (Luk, Green, Abutalebi, & Grady, 2012). Specifically, Luk and colleagues (2012) aggregated data obtained from ten bilingual language control experiments (e.g., cross linguistic picture naming, translation, interpretation: Abutalebi & Green, 2008; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Lehtonen et al., 2005; Rinne et al., 2000; Price, Green, & von Studnitz 1999; Wang, Kuhl, Chen, & Dong 2007) and identified nine regions that stably contribute to bilingual language control. These regions partially overlapped with those described in the ACH. Specifically, the evidence supported the hypothesized role of pre-SMA, left IFG, left DLPFC, right prefrontal (premotor specifically), and basal ganglia nuclei in bilingual language control, but did not find evidence for stable involvement of the ACC, parietal cortices or thalamus. The meta-analysis also identified a new region in the left medial temporal lobe that was consistently activated in bilingual language control tasks. One goal of the neuroimaging research conducted for my doctoral thesis was to better understand the neurocognitive basis of bilingual language control by exploring patterns of activation in these previously identified bilingual language control regions across different task manipulations.

One limitation of the ACH is that although it refers to the dual mechanisms framework of general cognitive control provided by Braver, Grady and Burgess (2007, but see also Braver, 2012), its descriptions of the neurocognitive bases of proactive and reactive control do not match those proposed by the authors. For instance, the dual mechanisms framework describes proactive control mechanisms as relying jointly upon goal maintenance in the prefrontal cortex and dopaminergic systems in the basal ganglia. In contrast, ACH proposes that goals are maintained by parietal cortices and that the basal ganglia are involved in language selection, switching, and planning (Abutalebi and Green, 2007). Additionally, reactive control in the dual mechanisms framework is either triggered by conflict detection in the ACC, or by associative memory retrieval in the temporo-parietal memory association areas. While the ACC is listed as a conflict monitoring region in the ACH, the medial temporal lobes, which were implicated by the meta-analysis in bilingual language control, are not mentioned in the ACH. Across the current three experiments, my research explores the neural (Experiments 1 and 3) and cognitive (Experiments 1, 2, 3) bases of proactive and reactive bilingual language control executed across global and local levels of language selection in early, proficient bilingual individuals.

To study bilingual language control, my research employed a novel research paradigm called Rapid Instructed Task Learning (RITL) that has been increasingly used to study non-linguistic cognitive control and in particular cognitive flexibility (Cole, Laurent, & Stocco, 2013; Stocco, Lebiere, O'reilly, & Anderson, 2012). Non-linguistic RITL paradigms have previously been used to study bilingual cognition (Beker, Prat, & Stocco, 2016), but prior to my work, such paradigms had not been used with linguistic stimuli to study bilingual language control. I argued that such studies offer two advantages over the predominant “naming” paradigms for studying bilingual language control. First, as opposed to typical cognitive paradigms in which one set of instructions is provided at the beginning of the experiment and subsequent trials vary only in the stimuli used, RITL paradigms enable the experimenter to reconfigure task rules in such a way that participants complete a different instruction on each trial. Such a design allows us to emulate the complex world of bilingual language use, in which different grammatical rules (local control) and different target languages (global control) must be used dynamically depending on the communicative context. Second, RITL paradigms allow us to provide separate instructions about each of these levels of selection, providing a mechanism for separately identifying local and global control processes. Third, with some training, rules for completing a task can be provided in a symbolic manner, allowing one to examine top-down control mechanisms without and contamination from bottom-up influences that receiving a stimulus in a particular language or grammatical form might bring.

Thus, each of the three experiments in my dissertation employed RITL tasks. Although each experiment had unique manipulations, all experiments included the following components: a “target language” phase in which the language to-be-used on a given trial (e.g., Spanish or English) was provided with some type of non-linguistic cue (e.g., a “#” or the English flag), a “rule selection” phase in which a morpho-syntactic rule (e.g., pluralize, past-tense) instruction was given with a non-linguistic cue, and an “execute” phase in which a variable, either a real or pseudoword, was provided. At this point, the bilinguals’ performed the instructed operation (e.g., pluralize in English) on the variable, creating a sub-vocal bilingual language production task. In all experiments, this was followed by a “probe verification” phase, in which participants had a short time to verify whether a given stimulus was correct or incorrect based on the instructions and variable given for a particular task. Figure 1 below shows a sample RITL trial from Experiment 1.

Figure 1.

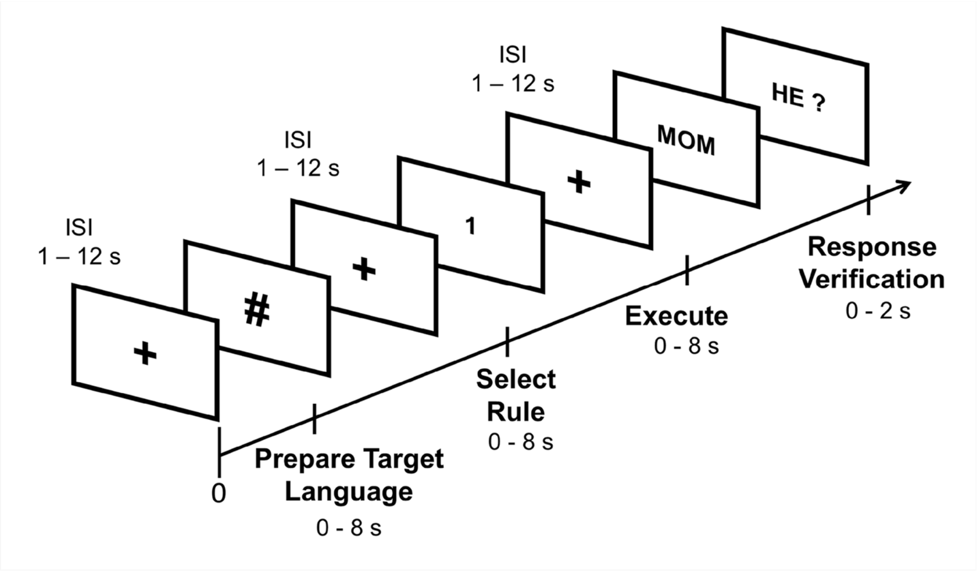

Figure 1. Schematic of a sample trial from the Rapid Instructed Learning Task Paradigm

Across the three experiments, I investigated the following questions: (1) whether morpho-syntactic rule processes in bilinguals use the same mechanisms as lexico-semantic control processes, (2) whether the *neural* mechanisms involved in global control and local control differ from one another; (3) whether the *cognitive* mechanisms underpinning global and local language selection differ from one another; and (4) whether bilinguals use both proactive and reactive control mechanisms during global and local language control. Three experiments addressing these questions, each of which has been accepted (Experiment 1), is under revision (Experiment 2) or has been submitted (Experiment 3) for publication, are included herein, in chronological order.

In summary, with a focus of morpho-syntactic production processes, my doctoral research program investigated the mechanisms by which bilingual individuals, who make up more than half of the population, execute the particular language control processes that are both unique to them (global control) and are shared between them and monolingual speakers (local control).

Chapter 2. Manuscript 1

The Bilingual Language Network: Differential Involvement of Anterior Cingulate, Basal Ganglia and Prefrontal Cortex in Preparation, Monitoring, and Execution

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2.1 Abstract

Research on the neural bases of bilingual language control has largely overlooked the role of preparatory processes, which are central to cognitive control. Additionally, little is known about how the process involved in global language selection may differ from those involved in the selection of words and morpho-syntactic rules for manipulating them. These processes were examined separately in an fMRI experiment, with an emphasis on understanding how and when general cognitive control regions become activated. Results of region-of-interest analyses on 23 early Spanish-English bilinguals showed that the anterior cingulate cortex (ACC) was primarily engaged during the language preparation phase of the task, whereas the left prefrontal (DLPFC) and pre-supplementary motor areas showed increasing activation from preparation to execution. Activation in the basal ganglia (BG), left middle temporal lobe, and right precentral cortical regions did not significantly differ throughout the task. These results suggest that three core cognitive control regions, the ACC, DLPFC, and BG, which have been previously implicated in bilingual language control, engage in distinct neurocognitive processes. Specifically, the results are consistent with the view that the BG "keep track" of the target language in use throughout various levels of language selection, that the ACC is particularly important for top-down target language preparation, and that the left prefrontal cortex is increasingly involved in selection processes from preparation through task execution.

Key words: anterior cingulate cortex, basal ganglia, bilingualism, cognitive control, prefrontal cortex, functional magnetic resonance imaging

2.2 Introduction

Bilingual language control refers to the set of mechanisms used for the selection and maintenance of a target language in the face of competing symbolic word representations and morpho-syntactic rules for manipulating them (Costa, Miozzo, & Caramazza, 1999; Hatzidaki, Branigan, & Pickering, 2011). Such control is likely underpinned by multiple processes, including the selection of the language to use at a given situation, the generation of linguistic goals (e.g., pluralizing a word based on the target language) and the selection of word forms and rules for manipulating words to achieve the goal (e.g., Guo, Liu, Misra, & Kroll, 2011; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2015; Hoversten, Brother, Swaab, & Traxler, 2015). As a result, bilingual language control likely involves multiple sub-component neurocomputations deployed across various situations (e.g., speaking a foreign language continuously while abroad vs. translating between individuals) and applied to different levels of selection (e.g., the need to speak in the Spanish language vs. the need to conjugate the verb *"hablar"* in Spanish). Many of these intricacies are yet to be addressed in the bilingual language control literature. The current study aims to advance understanding of the neurocognitive mechanisms of bilingual language control.

The role of general control mechanisms in bilingualism. The existing body of literature investigating the neural underpinnings of bilingual language use has widely implicated three regions known to be more broadly involved in cognitive control: the dorsolateral prefrontal cortex (DLPFC), the basal ganglia (BG), and the anterior cingulate cortex (ACC). In the first fMRI investigation of bilingual language switching, Hernandez, Martinez, and Kohnert (2000) used a picture-naming paradigm in which the target language either switched between Spanish and English or remained stable in either language within a block. The results showed that activation in the left DLPFC increased in the switching condition where competition for selection between two available languages became maximized. In a series of follow-up studies, Hernandez and colleagues replicated and extended their original findings, showing repeatedly that the DLPFC is specifically engaged when bilinguals are asked to switch between target languages as opposed to maintaining a particular language (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, 2009). This is consistent with the broad body of literature implicating the DLPFC in cognitive control. Specifically, when tasks involve response conflict of some kind (e.g., Mansouri, Tanaka, & Buckley, 2009) the DLPFC is involved in goal maintenance or storing a set of rules for behaving given specific conditions (Miller & Cohen 2001; Wallis, Anderson, & Miller, 2001; Cole, Bagic, Kass, & Schneider, 2010; Becker, Prat, & Stocco, 2016).

In parallel, evidence from neuropsychological (e.g., Abutalebi, Miozzo, & Cappa, 2000; Fabbro, 2001), neurosurgical (Robles, Gatignol, Capelle, Mitchell & Duffau, 2005), and neuroimaging (e.g., Crinion et al., 2006; Lehtonen et al., 2005) studies has implicated the BG, and particularly the caudate nucleus, in bilingual language control. The BG are a set of subcortical nuclei composed of the subthalamic nucleus, the substantia nigra, the external and internal segments of the globus pallidus, and the striatum. The striatum consists of the caudate and putamen, and serves as the input station of the circuit. The BG receive inputs from the entire cortex and modulate signals to prefrontal regions (including both DLPFC and ACC) in a manner well-suited for dynamically reprioritizing responses (e.g., Stocco, Yamasaki, Natalenko, & Prat, 2014; Stocco, Lebiere, & Anderson, 2010).

Importantly for cognitive control, the BG are rich in dopamine, and thus have been associated with cognitive flexibility more so than the DLPFC (Pasupathy & Miller 2005). Based on modeling work demonstrating “Conditional Routing” of signals to the prefrontal cortex through the BG (Stocco et al., 2010), Stocco et al. (2010) proposed a shared role for the BG, and the striatal nuclei in particular, in bilingual language control. According to the model, the BG actively mediate signaling to the prefrontal cortex according to the dynamically changing target language being used by a bilingual at any given time.

In their theoretical review paper, Abutalebi and Green (2007) discuss research on bilingual language production under the lens of general cognitive control mechanisms. This review and subsequent refinements from the group (Green & Abutalebi, 2013; Abutalebi & Green, 2016) included an important role for the ACC, which is generally characterized as a region that detects or monitors conflict (e.g., Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns et al., 2004), as well as for the DLPFC and BG. Specifically, they proposed that controlled language production in bilingual individuals involves the dynamic interplay between conflict monitoring in the ACC, executive functioning (including response selection and inhibition) in the DLPFC, language planning, selection, and switching executed by the BG, and maintenance of representations in working memory in the parietal lobe. In a subsequent neuroimaging investigation, Abutalebi and colleagues confirmed that the ACC and BG were involved in monitoring target language during a bilingual picture-naming task (Abutalebi et al., 2007). They continued to demonstrate that consistent conflict monitoring in bilingual individuals shapes the ACC both structurally and functionally in a way that gives rise to more efficient processing of conflict in non-linguistic tasks as well (Abutalebi et al., 2011).

In summary, research on the neural basis of bilingualism has repeatedly implicated the DLPFC, BG, and ACC in bilingual language control. The goal of the current study was to understand the role of bilingual language control regions in different phases of bilingual language control processing.

The role of proactive control in bilingualism. Cognitive control research has identified two classes of control mechanisms: *Proactive control*, which is deployed early, and typically makes use of predictive cues to guide information processing in a top-down and goal-oriented manner; and *reactive control,* which is largely driven by bottom-up processes that trigger a corrective function following unanticipated detection of conflict (e.g., Braver, Grey, & Burgess, 2007; Braver, 2012). The role of proactive control in bilingual language use has been largely ignored. For example, in a recent meta-analysis of the neural networks supporting bilingual language control (Luk, Green, Abutalebi, & Grady, 2012), none of the ten experiments employed paradigms in which language preparation could be investigated separately from language use. Interestingly, this meta-analysis did not find significant activation in the ACC across experiments. In the real world, however, bilinguals likely use predictive cues about which language they should speak, whether it be broad contextual cues such as the location (e.g., at home versus at work), previous experience with the individual they are speaking to, or subtler (and certainly less predictable) cues such as the ethnicity of a person they are about to interact with.

One recent experiment by Woumans et al. (2015) investigated the cognitive effect of preparatory processes on bilingual language control by training participants with faces that were reliably associated with particular language profiles. Each face was presented 2000 milliseconds before a speech event. Certain faces were reliably followed by speech in one language, while other “bilingual” faces were followed by speech in two languages. When given a noun in either language, participants were able to more rapidly produce associated verbs when a familiar face, regularly associated with speech in one particular language, served as the preparatory cue for a trial. In contrast, participants experienced more difficulty with the task when either an unfamiliar face, or a familiar bilingual face preceded the trial. These results are consistent with research on general cognitive control which has shown that predictive cues enable proactive adjustment for the desired subsequent task (Braver 2012; Sohn & Carlson, 2007; Ruge, Jamadar, Zimmermann, & Karayanidis, 2013; Zhang, Morris, Cheng, & Yap, 2013).

To the best of our knowledge, only one neuroimaging investigation to date has measured the role of preparatory cuing in bilingual language control. Reverberi et al. (2015) presented an abstract cue indicating "target language" in advance of a to-be-named picture. They found that language switching during preparation resulted in activation in the left middle temporal gyrus, right parietal lobe, and bilateral precuneus. In contrast, during task execution, the medial prefrontal cortex was more highly activated when target language switched than when it was repeated. Thus, when task preparation and execution were separately examined in a naming task, different sets of regions were implicated in different phases. The current paper aims to extend the existing research by investigating the neural mechanisms associated with preparatory cuing during a novel bilingual language task.

Investigating morpho-syntactic rule application in bilinguals. A second limitation of the existing bilingual control literature is that the majority of it has been limited to lexico-semantic selection processes, most commonly operationalized through picture-naming or picture-word-matching tasks. While lexical selection in the face of competing representations is clearly one of the demands placed on a bilingual language control system, such selection also occurs in morpho-syntactic processing. To the best of our knowledge, none of the switching paradigms typically used to study bilingual language control has included morpho-syntactic manipulations.

This is important to consider, however, as research has shown that co-activation of linguistic information in the bilingual brain is not limited to the lexico-semantic level (Pickering & Ferreira, 2008; Hatzidaki et al., 2011). Intersentential codeswitching and cross-linguistic structural priming provide additional evidence that the need to manage interference between languages extends to morpho-syntactic levels (Pickering & Ferreira, 2008).

Separating control processes from stimulus-driven associations. A third, but less pervasive, limitation of the existing bilingual control literature is that it is difficult to separate top-down linguistic control processes from any bottom-up influences that are driven by stimuli occurring in a particular language. It is likely that hearing or reading a word in a particular language will prime other related words in the same language and the rules for manipulating words in that particular language. Often in bilingual language control experiments, the target language itself is used to indicate which language a particular task should be executed in. For example, in their seminal bilingual language switching investigation, Hernandez, Dapretto, Mazziotta, and Bookheimer (2001) used the words "say" and "diga" presented simultaneously with a picture to instruct participants which language to name an object in. Similarly, in a Chinese-English switching task, Wang, Kuhl, Chen, and Dong (2009) used either a Chinese character "读" or the English counterpart 'read' to indicate which language a trial should be executed in. In the real world, bilingual language control, like any other cognitive control, involves dynamic interactions between top-down planning and attention allocation and bottom-up, stimulus driven biasing of information. However, including both types of information in a paradigm makes it complicated to understand what is driving behavior and brain activation. Therefore, the current paradigm uses non-linguistic, symbolic cues to attempt to isolate stimulus-driven effects from preparatory processes.

Rapid instructed task learning paradigm. The current paper addresses these three limitations through the development of a novel paradigm that allows: (1) the separation of preparatory processes from task execution, (2) the investigation of bilinguals' morpho-syntactic rule selection and application, and (3) the separation of top-down control structures from bottom-up linguistic influences. Specifically, we employed a variant of the Rapid Instructed Task Learning (RITL) paradigm, which is gaining popularity as a tool for understanding how the human brain executes rule-based behaviors (Stocco, Lebiere, O'Reilly, & Anderson, 2012; Cole, Laurent, & Stocco, 2013; Stocco & Prat 2014). One critical feature of the RITL paradigm is that the rules for completing a subsequent task are presented *before* the stimuli on which the rules need to be applied. This allows one to estimate the neural processes involved in dynamically constructing a mental program for controlled behavior *separately* from the execution of that behavior. In the current experiment, this design feature provides the ability to separate preparation from execution in bilingual language control, and to separate the top-down processes associated with generating a control structure from the bottom-up influences of linguistic stimuli. This separation allows one to investigate the control mechanism(s) that is established to perform a task without influence from the stimuli.

Predictions. Our predictions focus on three questions central to bilingual language control research that can be extracted using this novel research design: (1) How and when do general cognitive control regions participate in bilingual language control? (2) How do the neural networks involved in proactive control differ from those involved in bilingual language production? and (3) How do the neural networks involved in global language selection differ from those involved in morpho-syntactic rule selection?

To address these questions, the analyses conducted herein will be centered primarily upon the regions identified in a quantitative meta-analysis on the neurobiology of bilingual language control (Luk et al., 2012). Specifically, Luk et al. (2012) identified a network of brain regions that have been consistently reported in investigations of bilingual language control. This network includes regions discussed herein that are typically associated more generally with cognitive control including: DLPFC, BG (specifically bilateral caudate nuclei), and pre-supplementary motor areas (pre-SMA), also discussed by Abutalebi and Green as part of the ACC conflict monitoring network (Abutalebi & Green, 2016). Not surprisingly, the results also included regions more broadly associated with language processes such as the left inferior frontal gyrus (BA 44, 47) and the left middle temporal gyrus (BA 37). However, as our task does vary significantly from those reported in the meta-analysis, we also conducted exploratory, voxelwise, whole-brain analyses.

To address the first question, "How and when do general cognitive control regions participate in bilingual language control?" our primary analyses will investigate how activation changes in these regions of interest, defined a priori based on the meta-analysis, across the three task phases. Based on the Conditional Signal Routing Theory (Stocco et al., 2010; Stocco et al., 2014) and the results of Crinion et al. (2006), we predict that the BG will be consistently involved in tracking the target language throughout the different phases of a single trial. In contrast, we predict that brain activity in the DLPFC will increase as the trial progresses from language preparation to rule execution, due to increases in working memory demands. Finally, we predict that the ACC will be most highly activated during task execution, as it is believed to work in concert with the Pre-SMA and DLPFC to address response conflict (Abutalebi & Green, 2007; 2016; Becker et al., 2016)

To address the second question, “How do the neural networks involved in proactive control differ from those involved in bilingual language production?” we will compare patterns of whole-brain activation during language preparation to those obtained during task execution. Based on the research reported by Reverberi et al. (2015), we predict that posterior regions including the middle temporal gyrus, parietal lobes, and precuneus will be more active during preparation, whereas the medial frontal gyrus and all of the canonical left hemisphere language processing regions (e.g., Broca’s area in inferior frontal gyrus and Wernicke’s area in superior-posterior temporal gyrus) will be more active during execution, which involves the processing of linguistic stimuli. As previously discussed, we also predict that ACC and DLPFC will be more active during task execution.

Finally, to address the third question, “How do the neural networks involved in global language selection differ from those involved in morpho-syntactic rule selection?” we will compare patterns of whole-brain activation during target language preparation to those obtained during morpho-syntactic rule selection. In their review, Buchweitz and Prat (2013) suggested that linguistic rules are organized hierarchically in the bilingual brain, according to target language. Based on research showing that more abstract rules engage more rostral regions of the PFC (Badre, 2008; Koechlin, Ody, Kouneiher, 2003), Buchweitz and Prat (2013) proposed that target language may be represented more rostrally than morphosyntactic rules. Thus, we predict that both selecting target language and selecting morpho-syntactic rules will recruit the left lateral prefrontal cortex (and in particular the inferior frontal gyrus) but that global target language will recruit more rostral PFC regions.

2.3. Materials and Methods

Participants. Twenty-four, right handed Spanish-English bilinguals (20 females, aged 18-31 years) were paid for participation in the current study. Participants were required to be highly proficient in both languages (as assessed through grammatical proficiency tests) and to have learned both languages before the age of seven. Bilingual language experience information is summarized in Table 1.

All participants were also healthy, with no history of developmental or neurological disorders. All participants provided informed consent, consistent with the protocols approved by the University of Washington's Institutional Review Board. Data was removed from one participant due to excessive in-scanner motion, defined as more than 10% of images being removed for > 1mm rigid displacement between consecutive volumes. Data from the remaining 23 participants are reported herein.

Table 1

Language Characteristics of Bilingual Participants with Standard Deviations in Parentheses

	Spanish Mean (STDEV)	English Mean (STDEV)
Age of Acquisition	3.09 (2.25)	1.89 (2.29)
Self Rated Speaking Proficiency (10)	7.80 (1.07)	9.43 (0.88)
Self Rated Understanding Proficiency (10)	8.73 (1.17)	9.45 (0.58)
Self Rated Reading Proficiency (10)	7.41 (1.59)	9.43 (0.73)
Tested Grammatical Proficiency (50 Spanish, 20: English)	85.30 % (3.93)	90.90 % (1.56)

Materials. *Rapid Instructed Task Learning (RITL) paradigm.* In the current experiment, each RITL trial began with a preparatory symbolic cue indicating which language the trial was to be executed in. The neural activity associated with processing of this cue reflects the mechanism for preparing to speak in a target language and using this information to guide subsequent attention to word forms and rules within that particular language. After target language cuing, participants saw a code indicating which morpho-syntactic rule(s) they will be asked to apply. Again, this phase preceded any linguistic stimuli. Thus, neural activation during this phase should reflect the processes involved in selection of competing morpho-syntactic rules. To the best of our knowledge, no experiment to date has compared the processes involved in global, target language preparation from those involved in morpho-syntactic rule processing. The final phase of the task involved presentation of a word or a word pair on which the participants then performed the instructed rule. These words were always presented in the target language that was cued at the beginning of the trial (e.g., English). During this phase, participants performed the instructed manipulation (e.g., pluralize) on the stimulus provided (e.g., *dog*) and subvocally produced the word "*dogs.*" This phase of the current experiment shares the most features with existing bilingual language control research, as task execution in an instructed language is what is typically measured.

The RITL paradigm used in the current experiment consisted of 72 total trials, 36 in English and 36 in Spanish. The total of 72 trials were divided into 4 blocks of 18 trials, and each block contained 9 English and 9 Spanish trials (3 of each rule type), presented in pseudo randomized order. Languages were mixed within blocks and randomly varied from trial to trial. Each trial involved the presentation of information across three phases. The first "Prepare Target Language" phase consisted of a symbolic cue (# or *) which indicated that the next trial would be in either Spanish or English. Mapping between a particular symbol and a particular target language was counter-balanced across participants. The second "Rule Selection" phase of the task involved the presentation of one of three types of morpho-syntactic rules: rules for manipulating nouns (generate pronoun or pluralize), rules for manipulating verbs (conjugate past or future tense) and combined rules which consisted of all pairings of noun-verb manipulations (e.g., pluralize noun and conjugate past tense of verb). All rules were indicated with alphanumeric symbols that remained constant across languages ("1" and "2" for noun rules, and "A" and "B" for verb rules). Each type of rule was presented equally often (24 nouns, 24 verbs, and 24 noun-verb combinations) across the experiment. The third "Execution" phase of the experiment involved the presentation of words in either English or Spanish. The words were always presented in the same language cued by the "Prepare Target Language" instruction. All nouns and verbs chosen were highly frequent (top 5%) using both English and Spanish frequency norms (Wiktionary, 2017), with no significant differences in frequency between Spanish and English words ($p = 0.82$). They also all had regular conjugations. To best equate morphosyntactic processes across languages, nouns used for the pronoun rule had biological gender in both languages (e.g., grandmother, aunt). No word was presented in both its English and Spanish forms within participants, however all words occurred in both languages across stimulus lists, which were counterbalanced across participants. At the end of each trial, participants saw a "Response Verification Probe" which consisted of a word or word combinations that could be produced by applying the given rules to the presented stimuli. Half of the verification probes were *true*, or reflected the answer that would be achieved if the correct rules were applied to the stimuli presented, and the other half of the probes were *false*, corresponding to the answer that would be achieved if an incorrect rule was applied to the stimuli presented. Sample stimuli for Spanish and English trials are listed in Table 2.

Table 2

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

Handedness questionnaire. The Oldfield Handedness Inventory (Oldfield, 1971) was used to assess handedness of the participants. This survey includes 10 questions on which participants are asked to rate whether they do tasks using their left hand, right hand, or both hands equally. Handedness is then indexed as the relative proportion of right handed responses - left handed responses over the total number of right + left handed responses.

English proficiency measure. The English Grammatical Proficiency Test is a subtest of the "Examination for the Certificate of Proficiency in English" developed at the University of Michigan (English Language Institute, 2006). It has previously been used in bilingual investigations as a measure of English proficiency (e.g., van Hell & Tanner, 2012) as it is sensitive to subtleties in English grammatical proficiency. The subtest consists of 20 multiple choice questions and participants are given as much time as needed for completion.

Spanish proficiency measure. The Spanish Grammatical Proficiency test is a subtest of 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). This multiple choice, paper and pencil test has also been previously used to assess Spanish proficiency in bilingual research (e.g., Montrul & Bowles, 2009). Participants were given as much time as they needed to complete the test.

Bilingual language experience questionnaire. A modified version of the Language Experience and Proficiency Questionnaire (Marian, Blumenfeld, & Kaushanskaya, 2007) was used as a self-report measure of bilingual language experience and proficiency. The test asks participants to self-rate language comprehension, production, and reading proficiency, and also asks explicit questions about background language experience. The modified version of this test has been used to characterize language experience in studies investigating individual differences in bilingual language experience (e.g., Yamasaki & Prat, 2014).

Procedure. *Behavioral testing session.* All participants completed behavioral testing before the fMRI session, with no more than two days between practice and neuroimaging sessions. The behavioral session included completion of the Edinburgh Handedness Inventory (Oldfield, 1971) and the language proficiency and experience measures above, in addition to two individual differences measures collected on all participants in our lab, but not relevant for the study reported herein (Operation span: Unsworth, Heitz, Schrock, & Engle, 2005; and Nelson-Denny Reading Test: Brown, 1960).

Following completion of these tasks, participants received systematic training on the RITL paradigm used for this experiment. The practice session was composed of a memory task in which participants memorized which language and which rules were associated with each symbol. Importantly for the current experiment, memory training for the RITL task was completed using instructions written in both Spanish and English. The memory task involved showing each of the code-rule pairs (e.g., "# - Spanish") 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 is given. In order to complete the practice memory task, the participants had to reach a criterion of accurately identifying the same code at least two times consecutively. After completing the memory task, each participant completed 16 practice RITL trials. In the practice trials, participants were given explicit feedback on their performance including accuracy and response times to help ensure that they understood the task and could successfully perform it in the scanner. Altogether, the total behavioral session took 1.5 hours.

fMRI data acquisition. Data were collected using a 3.0 T Philips Achieva scanner at the Integrative Brain Imaging Center operated by the University of Washington. The study was performed with a gradient echo planar pulse sequence with TR = 1,000 ms, TE = 30 ms, a 60° flip angle and field of view = 240 mm. Seventeen oblique-axial slices were imaged, and each slice was 5-mm thick aligned to the anterior commissure-posterior commissure with a gap of 1 mm between slices. The acquisition matrix was 64 × 64 with an in-plane resolution of 3 × 3 mm voxels. For most participants, this did not constitute full coverage, and no data was collected from the most rostral and ventral parts of the temporal lobe, as well as from the regions surrounding the vertex. In the neuroimaging analysis procedures, any predefined region of interest that was not completely covered in all participants was excluded.

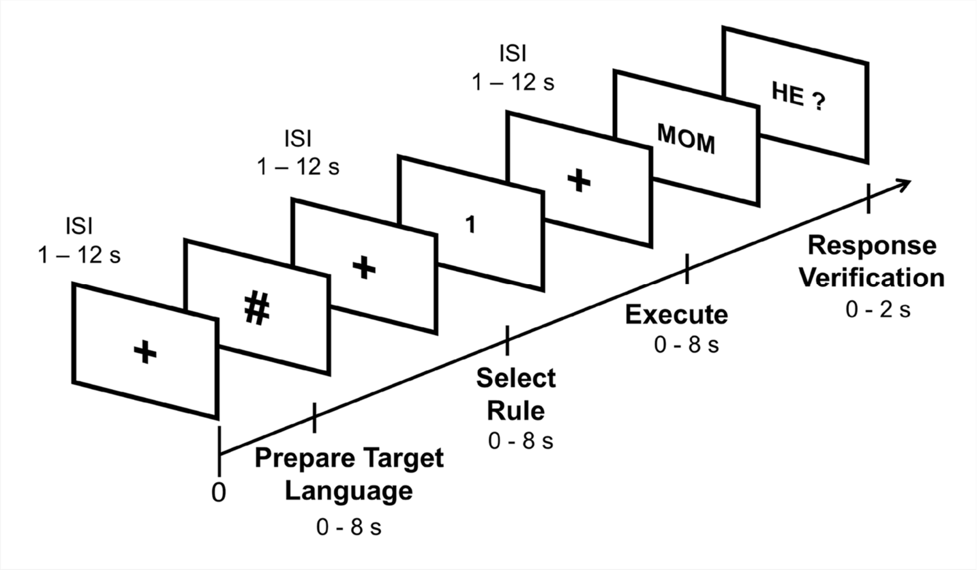
RITL paradigm presentation. As is typical of RITL paradigms, presentation of all three phases were self-paced. Participants were instructed to press a button when they were finished encoding instructions (i.e., during the Prepare Target Language and Select Rule phases). During the Execute phase, participants were instructed to press a button after they had transformed the word(s) presented according to the rule(s) specified by the task. If no response was initiated within 8 seconds during Prepare Target Language, Select Rule, or Execute phases, the trial "timed out" and automatically advanced to the next phase (this occurred in 2% of the data). The duration of the *time out* window was calculated based on pilot data as the value that contained all correct behavioral responding across the three phases in behavioral data collected out of the scanner.

Each trial ended with a verification probe. As is typical with RITL paradigms, the purpose of the verification probe is to ensure that participants are mentally generating the correct answer during the Execute phase. Thus, participants have only 2 seconds to respond YES for correct or NO for incorrect answers during the verification probe. To do so, they pressed a button with the hand corresponding to the position of the YES or NO labels on the screen. The position of the response labels was counterbalanced across participants. Accuracy to the verification probe is used to indicate which trials to use in subsequent analyses, however neural data is not analyzed during the verification phase.

To assess neural responses to the three critical task phases, each phase was separated from one another by delays with randomly varied durations between 1 and 12 seconds, according to an exponential distribution that optimizes parameter estimation (Dale, 1999). The purpose of these delays is to reduce the collinearity between phases, and allowed for better estimation of the brain activity corresponding to each phase. A schematic of a RITL trial presentation is depicted in Figure 1.

Figure 1

Schematic of a sample trial from the Rapid Instructed Learning Task Paradigm



fMRI preprocessing. The data were first preprocessed using SPM8 (Wellcome Trust Centre for Neuroimaging, Cambridge, UK). All functional volumes were corrected for slice timing acquisition, realigned to the first image within each run, normalized to the Montreal Neurological Institute (MNI) template, resampled to 2 mm^3 voxels, and smoothed using an 8 mm Gaussian kernel.

ROI analyses. To best integrate our results with those reported in the meta-analysis of Luk et al. (2012), which is reflective of the literature on bilingual language control at large, nine spherical regions of interest (ROIs) were used for ROI analyses. Centroids were converted from Talairach space to MNI space using Ginger ALE 2.3.3 (using the algorithm proposed by Brett, Christoff, Cusack, & Lancaster, 2001). As the current experiment was critically interested in the ACC and BG, we added two additional regions that *did not reach significance* in the review paper, namely the left caudate nucleus and the anterior cingulate cortex (ACC). The size, reference from which the ROIs were drawn, original coordinates reported, MNI coordinates of the centroids, and corresponding Brodmann's areas (where applicable) of the nine ROIs used herein are listed in Table 3.

Table 3

Description of Regions of Interest (ROIs) Used for Neuroimaging Analysis

Region	Reference	Original Coordinates	Centroid MNI coordinates	BA	Radius (mm)
Left DLPFC	Luk et al. (2012) (Talairach Coordinates)	-46, 18, 26	-44, 13, 29	46	8
Left Inferior Frontal	Luk et al. (2012) (Talairach Coordinates)	-50, 18, 6	-48, 15, 11	44	8
Left Lateral Orbitofrontal	Luk et al. (2012) (Talairach Coordinates)	-32, 20, -8	-31, 18, -2	47	8
Left Middle Temporal	Luk et al. (2012) (Talairach Coordinates)	-50, -44, -6	-48, -42, -6	37	8
Pre-SMA	Luk et al. (2012) (Talairach Coordinates)	2, 8, 58	1, 1, 57	6	10
Right Precentral	Luk et al. (2012) (Talairach Coordinates)	44, -4, 30	40, -9, 32	6	8
Right Caudate	Luk et al. (2012) (Talairach Coordinates)	16, 8, 12	14, 5, 16		6
Left Caudate	Left homologue of Luk et al. (2012) right caudate	-16, 8, 12	-14, 5, 16		6
ACC	Abutalebi et al. (2012) (MNI Coordinates)	0, 6, 44	0, 32, 24		10

Summary statistics for the ROI analyses were generated by averaging across the parameter values (i.e., beta weights) of all voxels within the ROI. Summary statistics were calculated independently for each combination of ROI, subject, and each of the three critical task phases (Prepare Target Language, Select Rule, Execute). The data were then analyzed separately for each ROI using one-way analyses of variance (ANOVAs), using the three task phases as the nominal levels of a single factor and subjects as the random factor. All effects were tested at a Bonferroni corrected significance level for 9 comparisons ($p < .0056$). Data from one participant was removed from the pre-SMA analysis as their slice prescription did not include the whole ROI.

Exploratory distribution of activation analyses. To examine the distribution of activation during the three critical task phases, statistical analyses were performed on individual and group data using the general linear model (GLM) implemented in SPM8 (Penny, Friston, Ashburner, Kiebel, & Nichols, 2007). Eight independent regressors were created corresponding to Preparation of Target Language, Rule Selection, Execution, and Verification phases in Spanish and English. Three types of analyses were conducted on the distribution of activation data. First, neural activity for the three critical task phases was estimated by collapsing across English and Spanish trials. Only trials in which participants responded correctly to the response verification probes were analyzed. Second, to address the three critical questions of interest, four statistical contrasts were computed between the three conditions (Prepare Target Language > Execute, Execute > Prepare Target Language, Prepare Target Language > Select Rule, and Select Rule > Prepare Target Language). Third, disjunction analyses were performed with the goal of determining patterns of activation *unique* to each of the four contrasts reported above. To do so, we started with the statistical contrasts reported above, and masked out any voxel that was active at a liberal threshold *(p = .001 uncorrected)* in the comparison or baseline condition. For instance, to determine which voxels were uniquely active in preparation, controlling for execution, any voxel active during Execution was removed from the contrast of Prepare Target Language > Execution. These analyses were modeled after those reported in Nee and Jonides (2013). For each analysis, group-level models were generated using the parameter estimates of first-level models as the summary statistics, and subjects as the random factor. To correct for multiple comparisons, all the results are reported after a family wise error (FWE) correction procedure at the voxel level, as implemented in SPM8, with corrected $p < 0.05$ and an extent threshold of 14 contiguous voxels to make sure that no cluster was found that was smaller than the smallest cluster that could be identified in native voxel space.

2.4. Results

Behavioral results. Accuracy rates to the response verification probes were high across participants (*M* = 88.5 %, *SEM* = 1.76%). Response times for correct trials were analyzed using a one-way repeated measures analysis of variance (ANOVA) with three within-participants task phases: Prepare Target Language (mean = 1547.57 ms, sem = 34.93), Select Rule (mean = 2726.83 ms sem = 47.69, and Execute (mean = 2953.33 ms, sem = 49.60). A significant main effect of task phase was revealed (F (2,66) = 57.570, $p < 0.0001$). Follow-up analyses showed that response times for Prepare Target Language were significantly shorter than for either Select Rule ($t(22) = -12.684$, $p < 0.0001$) or Execute ($t(22) = -9.017$, $p < 0.0001$) phases.

Another follow up analysis was conducted to compare performance across Spanish and English trial types. No significant differences were observed in response times across the three task phases ($p > 0.4$); however a comparison of task accuracies using Fisher's exact test revealed a marginally significant trend towards better accuracy on English trials ($p = .08$).

Region of Interest analyses. A significant main effect of task phase was observed in five of the nine ROIs: the anterior cingulate cortex (ACC), left dorsolateral prefrontal cortex (DLPFC), left lateral orbitofrontal cortex (BA 47), left inferior frontal gyrus (BA 44), and the pre-supplementary motor area (pre-SMA). Follow-up analyses showed that these phase-sensitive regions showed two different patterns of activation across the three tasks phases. Specifically, the ACC alone was significantly more active during the Prepare Target Language phase than during either Rule Selection or Execution phases, with the parameter estimates for the latter two being not significantly different than zero. In contrast, the three left frontal regions (left DLPFC, left orbitofrontal, left inferior frontal) and pre-SMA ROIs all showed significantly higher activation during the Execution phase than during the Prepare Target Language phase (with Rule Selection typically in between the two levels). Activation in the remaining four ROIs (bilateral caudate nuclei, left middle temporal gyrus, and right precentral gyrus) was not modulated by task phase, remaining constant across the task. *F*-statistics and follow up paired *t*-statistics are reported in Table 4. In summary, the ROI results suggest three unique patterns of activation across bilingual language control task phases: Preparatory Activation (greatest activation during preparation of target language), Execution Activation (activity that increases across task phases with highest activation during task execution), and Stable Activation (consistent activation across task phases). Patterns of activation in representative Preparation (ACC), Execution (DLPFC) and Stable (caudate) ROIs are depicted in Figure 2.

Table 4

Statistics from One Way Repeated Measures ANOVA Analysis on Regions of Interest, and Follow up t-Tests

Repeated Measures ANOVA Analysis	*df*	*F*	*MSE*	*p*
(A) Significant Main Effect of Phase				
Anterior cingulate cortex (ACC)	2	8.82	0.30	< .001
Left dorsolateral prefrontal cortex (DLPFC, BA 46)	2	25.50	0.41	< .001
Left lateral orbitofrontal cortex (BA 47)	2	15.32	0.12	< .001
Left inferior frontal gyrus (BA 44)	2	36.45	0.19	< .001
Presupplementary motor areas (pre-SMA)	2	6.10	0.34	0.005
(B) Nonsignificant Main Effect of Phase				
Left caudate nucleus	2	1.56	0.12	0.214
Right caudate nucleus	2	1.50	0.11	0.233
Left middle temporal gyrus (BA 37)	2	1.67	0.04	0.200
Right precentral gyrus (BA 6)	2	1.95	0.06	0.155

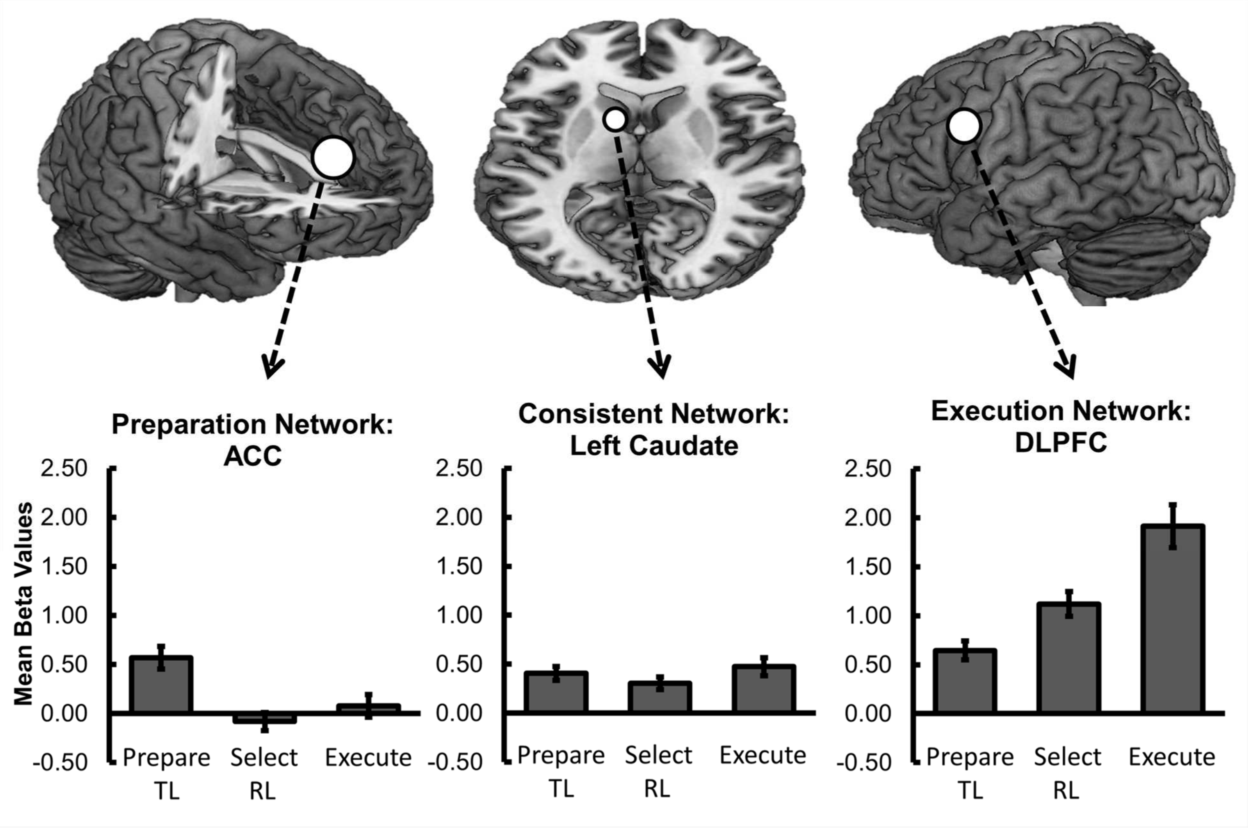
Follow-up Analysis (Paired Sample *t*-Test)	*df*	*t*	*p*
ACC			

Prepare Target Language > Select Rule	22	3.77	0.001
Prepare Target Language > Execute	22	3.32	0.003
DLPFC			
Prepare Target Language > Select Rule	22	-3.14	0.005
Prepare Target Language > Execute	22	-5.83	< .001
Select Rule > Execute	22	-4.79	< .001
Left lateral orbitofrontal cortex (BA 47)			
Prepare Target Language > Execute	22	-4.50	< .001
Select Rule > Execute	22	-5.20	< .001
Left inferior frontal gyrus (BA 44)			
Prepare Target Language > Execute	22	-7.42	< .001
Select Rule > Execute	22	-6.65	< .001
pre-SMA			
Prepare Target Language > Execute	21	-3.23	0.004

Note. Follow up analysis (paired sample *t*-tests) was run only where applicable. Degrees of freedom in pre-SMA analyses reflect the fact that one less participant was included in this analysis due to lack of coverage of the ROI in acquisition.

Figure 2

Mean beta weights extracted across the three task phases from three regions that elicit different patterns across phases (ACC: Anterior Cingulate Cortex, DLPFC: Left Dorsolateral Prefrontal Cortex)



Exploratory distribution of activation analyses. Voxel wise patterns of activation obtained from general linear model (GLM) estimates during the Prepare Target Language, Select Rule, and Execution phases, and statistical contrasts between these phases are described in the subsequent sections.

Prepare Target Language. GLM analysis revealed that preparing to use a target language resulted in the recruitment of a bilaterally distributed network including medial regions such as the ACC (BA 24 & 32), SMA, pre-SMA (BA6), bilateral caudate nuclei, the left lateral prefrontal cortex (BA 44) and bilateral parietal regions (Table 5A). It is interesting to note that many of the regions typically associated with bilingual language control were activated during the preparatory phase of the task, in which no linguistic information was presented, and no task was being executed.

Select Rule. In contrast, the Select Rule phase recruited a more left-lateralized pattern of activation. Specifically, the activation was centered around the superior portion of the inferior frontal gyrus in the left hemisphere, extending into middle and superior frontal regions and into the precentral gyrus. Activation in bilateral BG and parietal regions was also observed (Table 5B).

Execute. As predicted, the inferior frontal gyrus (classic Broca's area or BA 44/45) was highly active during bilingual rule execution. This cluster of activation extended medially into insular cortex and BG regions. Bilateral parietal and occipital activation were also observed (Table 5C).

Table 5

Centroids, Cluster Descriptions, and Statistics for Patterns of Activation in Three Task Phases (Prepare Target Language, Select Rule, and Execute)

				MNI coordinates		
Regions	Peak Brodmann's Area	Cluster Size	Peak T Value	x	y	z
(A) Prepare Target Language						
Bilateral anterior/middle cingulate, Dorsolateral prefrontal, SMA	24	734	10.76	-10	6	52
Left precentral	4	277	7.79	-42	-6	24
Left postcentral	3	885	9.27	-54	-20	26
Left basal ganglia, insula, inferior frontal		1850	9.31	-20	2	18
Left superior/middle frontal		125	8.47	30	40	4
Left inferior parietal	40	618	9.98	-38	-56	42
Left superior temporal, parietal	39	158	7.01	-40	-48	12
Left hippocampus		50	6.88	-30	-30	4
Left inferior occipital	37	20	6.98	-50	-72	-4
Right precentral	6	41	7.86	44	-6	24
Right cingulate	23	177	6.90	2	-34	28
Right superior parietal	7	472	8.03	38	-66	52

Right superior/ frontopolar/ dorsolateral frontal	10	56	6.55	22	56	16
Right basal ganglia		381	8.05	18	6	14
Right temporal	41	307	7.81	34	-30	0
Right inferior temporal	37	51	7.64	44	-70	-4
(B) Select Rule						
Bilateral SMA, middle cingulate, DLPFC, superior/medial frontal,	6	926	11.39	-6,	4	54
Left precentral	4	48	8.60	-32	2	60
Left thalamus, pre/post central, posterior cingulate, dorsolateral prefrontal, inferior frontal, insula, striatum		2868	9.99	-12	-20	8
Left insula	13	43	7.16	-46	6	2
Left caudate nucleus		35	7.58	-6	24	2
Left superior parietal	7	23	7.61	-12	-74	44
Left inferior parietal/supramarginal	40	419	8.94	-32	-52	42
Right precentral, caudate nucleus		617	8.68	32	-10	28
Right caudate nucleus		17	6.43	4	18	8
Right medial globus pallidus		17	7.74	14	-4	-2

Right thalamus		262	8.20	16	-20	10
Right middle occipital	18	43	7.44	30	-94	2
(C) Execute						
Left inferior frontal, insula, superior/middle frontal, pre/postcentral, putamen, temporal	44, 45	3492	12.77	-42	14	18
Bilateral supplementary motor area, bilateral medial superior, bilateral dorsolateral frontal, right anterior/middle cingulate, superior, medial frontal	6	1606	9.74	-6	6	56
Left precentral	6	56	6.83	-30	0	58
Left striatum		383	7.62	-20,	-2	2
Left thalamus		184	7.50	-10	-18	4
Left middle temporal	21	17	6.63	-58	-42	-6
Left parietal, middle occipital	40	931	9.55	-30	-66	48
Left middle occipital	18	136	8.00	-24	-96	2
Right middle frontal		140	7.81	38	6	60

Right insula	13	106	6.84	32	24	0
Right striatum		275	7.82	12	2	-2
Right parietal	7	194	6.77	32	-56	44
Right calcarine	18	219	10.10	26	-96	2

Note. MNI = Montreal Neurological Institute.

Preparation of Target Language versus Execution. A statistical contrast between Prepare Target Language and Execution phases showed that preparing to use a language resulted in significantly greater activation in medial regions including anterior frontal (BA 10), anterior cingulate (BA 24), middle and posterior cingulate (BA 23), and precuneus regions. Additionally, greater activation was observed in the temporo-parietal junction in the left hemisphere (roughly Wernicke's area, BA 39) as well as in its right hemisphere homologue. Activation was also higher in the right middle temporal gyrus during the Prepare Target Language Phase (Table 6A). Disjunction analysis showed that the majority of these regions were also uniquely active during target language preparation (Table 6B).

In contrast, the primary cluster that was significantly more active during Execution than during the Prepare Target Language phase encompassed the left inferior and orbital frontal regions (BA 44, 45 & 47), including Broca's area. Bilateral occipital cortex was also more active during execution, likely due to the fact that in this phase participants were viewing more complex visual stimuli (words) as opposed to single symbols (Table 6C). Disjunction analysis showed that one region in the left inferior frontal gyrus and occipital regions were uniquely active in the Execution phase when Preparation was controlled for (Table 6D).

Figure 3

Statistical contrasts for Prepare Target Language > Execute (in red) overlaid on the opposite contrast, Execute > Prepare Target Language (in blue)

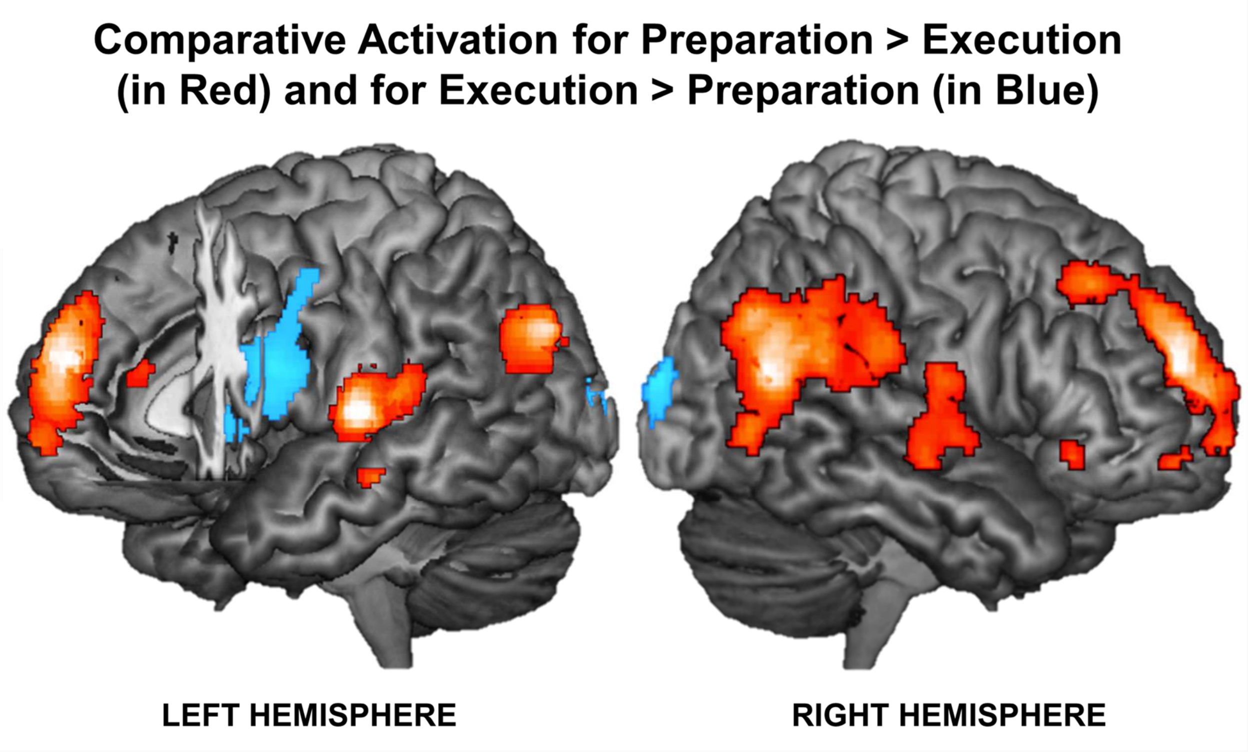


Table 6

Centroids, Cluster Descriptions, and Statistics for Contrasts and Disjunction Analyses between Prepare Target Language and Execute Phases

				MNI Coordinates		
Regions	Peak Brodmann's Area	Cluster Size	Peak T Value	x	y	z
(A) Prepare Target Language (TL) > Execute						
Bilateral superior and medial frontal, anterior cingulate	10	9.97	1512	18	54	20
Bilateral precuneus, posterior cingulate, middle cingulate, left cuneus		13.54	1192	-8	-60	36
Left superior temporal/supramarginal, insula, post central	22	10.07	1103	-52	-12	4
Left angular	39	9.10	383	-50	-70	30
Left middle temporal	21	7.46	15	-64	-12	-14
Left fusiform, parahippocampal		6.60	16	-38	-42	-10
Median cingulum		6.85	116	0	-26	42
Right anterior cingulate cortex		6.53	26	2	36	18
Right precentral	43	7.22	397	56	-6	14

Right orbitofrontal	47	7.11	14	48	30	-8
Right middle orbitofrontal	10	6.97	19	30	58	-8
Right temporal, supramarginal, inferior parietal, middle occipital	40	9.70	1616	60	-58	16
(B) Prepare TL > Execute (mask out. Execute)						
Bilateral anterior cingulate		26	6.53	2	36	18
Left superior temporal, post central	22, 40	1103	10.07	-52	-12	4
Left angular	39	383	9.1	-50	-70	30
Left precuneus		1192	13.54	-8	-60	36
Left middle temporal	21	15	7.46	-64	-12	-14
Right superior frontal, medial frontal		1512	9.97	18	54	20
Right post central	43	397	7.22	56	-6	14
Right inferior frontal	45	14	7.11	48	30	-8
Right middle frontal	10	19	6.97	30	58	-8
Right temporal		1616	9.7	60	-58	16

(C) Execute > Prepare TL						
Left inferior frontal, precentral	44	8.03	650	-46	12	18
Left insula	13	6.73	51	-30	24	2
Left middle occipital	18	8.04	149	-20	-94	8
Right superior occipital	18	8.28	169	22	-96	16
(D) Execute > Prepare TL (mask out. Prepare TL)						
Left inferior frontal		137	7.73	-56	24	20
Right cuneus		167	8.28	22	-96	16

Note. MNI = Montreal Neurological Institute.

Selection of target language versus morpho-syntactic rule selection. A statistical contrast between the two types of task preparation indicated that activation was greater in the Prepare Target Language phase in the bilateral precuneus and middle temporal/supramarginal regions as well as in bilateral rostral and medial prefrontal regions, and bilateral temporo-parietal junctions (Table 7A and Figure 4). Disjunction analyses showed that the majority of these regions were *uniquely* active during global target language selection, when morpho-syntactic rule selection was controlled for. There were no areas in which morpho-syntactic rule selection resulted in greater activation than did global target language selection.

Figure 4

Statistical contrasts for Prepare Target Language > Select Rule

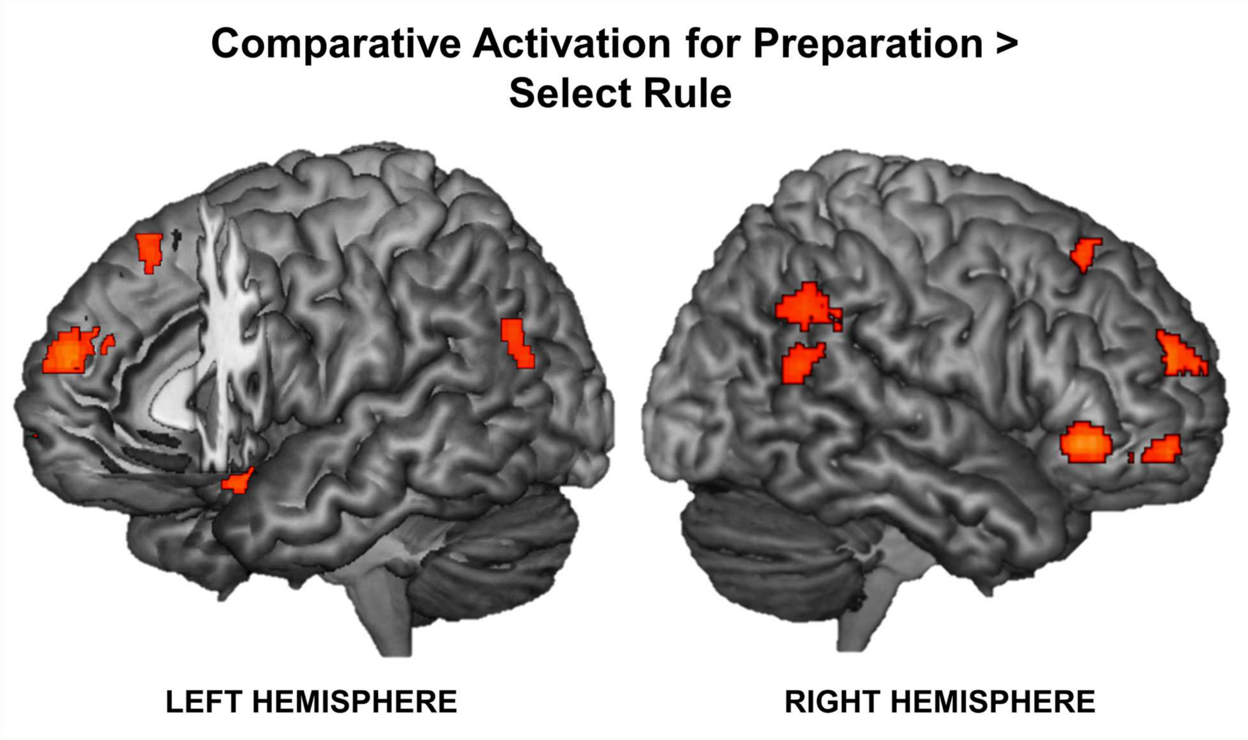


Table 7

Centroids, Cluster Descriptions, and Statistics for Contrasts and Disjunction Analyses between Prepare Target Language and Select Rule

				MNI Coordinates		
Regions	Peak Brodmann's Area	Cluster Size	Peak T Value	x	y	z
(A) Prepare Target Language (TL) > Select Rule (RL)						
Bilateral precuneus	7	6.96	33	-6	-60	38
Left Inferior Frontal, Left Insula	47	6.66	28	-32	20	-18
Left superior temporal/Supramarginal	39	6.45	37	-58	-58	28
Right inferior orbitofrontal	47	7.48	100	48	32	-6
Right superior, medial, dorsolateral frontal	46	7.27	218	18	54	20

Right middle orbitofrontal	10	6.93	36	34	58	-8
Right superior frontal		6.58	41	18	30	52
Right angular		6.54	69	60	-50	36
Right superior temporal		6.64	64	56	-52	18
(B) Prepare TL > Select RL (mask out. Select RL)						
Left inferior frontal		28	6.66	-32	20	-18
Left superior temporal	39	37	6.45	-58	-58	28
Left precuneus		33	6.96	-6	-60	38
Right superior frontal, medial frontal	10, 9	218	7.27	18	54	20
Right superior frontal		41	6.58	18	30	52
Right middle frontal	10	36	6.93	34	58	-8
Right inferior frontal		100	7.48	48	32	-6
Right supramarginal		69	6.54	60	-50	36

Right superior temporal	10	64	6.64	56	-52	18

Note. MNI = Montreal Neurological Institute.

2.5. Discussion

The results from this experiment highlight the complexity of the information processing demands associated with bilingual language control. Specifically, they show that when top-down preparatory processes are investigated prior to linguistic task execution, and in the absence of bottom-up linguistic cues, distinct patterns of involvement emerge for the three core cognitive control regions (ACC, BG, and DLPFC), as well as from the broader network of regions previously implicated in bilingual language control. Below we organize our discussion of the current results around our three research questions.

How and when do general cognitive control regions participate in bilingual language control? Our prediction for stable involvement of the BG across task phases was confirmed by the experimental results reported herein, which showed consistent activation of the bilateral striatum across task phases. These predictions are discussed in further detail in a review which proposes that the striatum is involved in "keeping track" of the target language a bilingual intends to communicate in, and uses this as a dynamic variable to route relevant, target-language-specific information to prefrontal cortex for subsequent processing (Stocco et al., 2014).

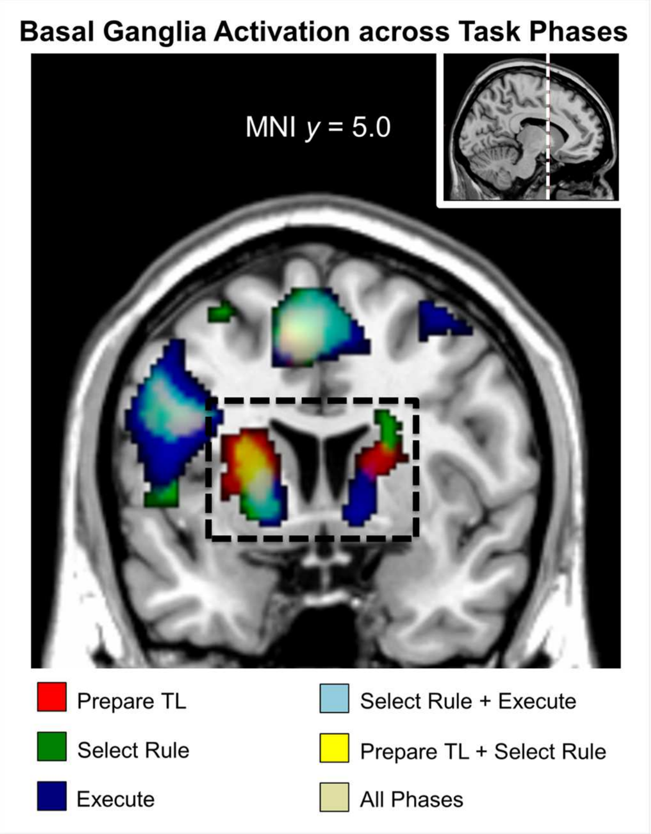
The idea that the striatum is involved in keeping track of which language a bilingual is using is consistent with previous research suggesting that language membership (e.g., English versus Spanish) is a feature of words in the bilingual brain that is accessible immediately, even before subsequent semantic category information (Hoverston et al., 2015). Given the priority of this information, it follows that the brain likely has a mechanism for determining which language a word form belongs to. Crinion's results from automatic within- and across-language semantic priming strongly suggest that the basal ganglia, and in particular the left caudate nucleus, is likely the center of such a language tracking mechanism (Crinion et al., 2006).

In the paradigm used for the current study, it is important to note that each phase of the task requires accessing *target language specific* information. During the Prepare Target Language phase, participants are first given the variable target language, and must store the current target language in memory. The subsequent Rule Selection phase requires that bilingual participants select the relevant rule for transforming a noun or verb based on the given target language. For instance, given the rule 1 (pronoun rule), bilinguals need to retrieve the appropriate rule for generating a feminine or masculine pronoun in either English (*she/he*) or Spanish (*ella/el*). Finally, during the Execution phase, participants are given a word in the target language, and must conjugate it according to language-specific rules previously provided. Although these phases likely involve different computations, each would require some kind of parameter setting based on the target language of a given trial.

Interestingly, although equivalent activation levels were observed in bilateral striatal ROIs across phases, the different task phases did elicit spatially distinct regions within the basal ganglia circuit, especially in the right caudate nucleus. To illustrate, Figure 5 depicts overlaid patterns of striatal activation for Preparation (in red), Rule Selection (in green), and Execution (in blue) with additive colors indicating overlap.

Figure 5

Statistical activation maps depicting overlaid patterns of activation across the three task phases in the basal ganglia (left hemisphere located on left)



As is illustrated by the large white region in the left caudate, these patterns of activation were highly overlapping in the left hemisphere; whereas, in the right caudate, the patterns of activation were more distinct across phases. These results may suggest that, consistent with the work of Crinion et al. (2006), and with the proposal made by Stocco and colleagues (2014), the left caudate keeps track of target language. The right caudate, on the other hand, has been suggested to be involved in inhibitory control or in overriding competing responses (e.g., Aron, 2011). Thus, it is possible that specific inhibitory control mechanisms are enacted at each task phase, based on the nature of information being blocked or gated to the prefrontal cortex. Consistent with this explanation, the right prefrontal region was also engaged in all task phases. We see the exploration of the role of the right caudate nucleus in bilingual language control as an important and interesting area for future investigation.

The results described herein also extend those initially reported by Hernandez et al. (2000) on the role of the DLPFC in bilingual language control. Consistent with our predictions and with previous research, we show that the DLPFC is activated during the sub-vocal production phase of our task. Our results extend those from previous research in two ways: (1) by showing that the DLPFC is active even under conditions in which task switching is not required, and (2) by showing that the DLPFC is also activated as the instructions for completing a task are sequentially presented, with the greatest activation occurring during task execution.

The DLPFC has been widely implicated in models of top-down cognitive control (e.g., Miller, 2000; Duncan, 2010; Braver, 2012), and the task used in this study was designed to isolate this form of control from the bottom-up influence of linguistic stimuli. It is possible that the increasing DLPFC activation across trials represents “goal maintenance,” as the instructions for completing each trial are presented incrementally across the phases of the RITL task. It is also possible that the increase in activation across task phases may reflect an increase in working memory load, as participants must hold an increasing amount of information in mind in order to execute the appropriate rule (e.g., Cole & Schneider, 2007; Irlbacher, Kraft, Kehrer, & Brandt, 2014). These findings are also consistent with research showing patterns of increasing activation in DLPFC with increased working memory as indexed by number of items to-be-remembered (e.g., Smith & Jonides, 1999).

It is important to note that the same increasing activation pattern was also observed in the left inferior frontal gyrus (BA44, BA47) and in the pre-SMA. The fact that the left inferior frontal gyrus was most active during morpho-syntactic rule execution is not particularly surprising, given its known role in both lexical selection (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997.; Vitello & Rodd, 2015) and morpho-syntactic rule related processes (Newman, Just, Keller, Roth, & Carpenter, 2003; Buchweitz & Prat, 2013). However, the pre-SMA has largely been proposed to be involved in conflict monitoring, perhaps proactively (Luk et al., 2012), and is often considered to work in concert with the ACC (e.g., Green & Abutalebi, 2013; Abutalebi & Green, 2016); this is surprisingly inconsistent with the pattern of results observed in the current experiment, which shows a rare dissociation of patterns of ACC and pre-SMA involvement. We see this as an interesting area for future research. Taken together, our results suggest that the DLPFC is part of a network of regions including the left lateral prefrontal cortex and pre-SMA that are most active during bilingual task execution.

It is unclear from our investigation, however, whether these prefrontal regions are engaged in the same neurocognitive processes, or implement different mechanisms that yield similar results in the current paradigm. In fact, recent bilingual language control models propose that left and right prefrontal regions may play different roles in language control (Abutalebi &

Green, 2016). Although the current study did not have a right frontal ROI, both whole brain and ROI analyses suggested that left inferior and middle frontal regions were more active during execution than during preparation. In contrast, the whole brain analyses suggest that the right inferior frontal gyrus was more active during preparation than either during execution (Figure 4) or rule selection (Figure 5). These results are somewhat consistent with the idea put forth by Abutalebi and Green (2016) that the left inferior frontal regions are involved in language selection and the right inferior frontal regions are involved in response inhibition. Within this framework, our results suggest that selection and inhibition happen at different levels, with selection processes happening throughout the task on increasingly specific subsets of information (e.g., language, rule, item) and inhibition happening primarily at the global level (language). We see this as an interesting first step toward answering the question put forth in the same paper about whether "language control is exerted at a single level or at multiple levels." (Abutalebi & Green, 2016, p. 694).

The results on the role of the ACC in bilingual language control were contrary to our predictions. They suggested that the ACC was uniquely active during target language preparation (or global language selection). Specifically, our results extend and refine previous research on the role of the ACC in bilingual language control by showing that: (1) the ACC is active during target language preparation, even when it precedes task execution, (2) the ACC was the only predefined ROI that was more active during target language preparation than during execution, and (3) ACC activation was not tied specifically to language switching.

A considerable amount of research has investigated the role of the ACC in domain-general cognitive control (e.g., Botvinick et al. 1999). Specifically, ACC activation is reliably observed in tasks involved in monitoring cognitive conflict such as overriding prepotent response and selecting a target among competing inputs (Badgaiyan and Posner 1998; Carter et al. 1998; Carter et al. 1999; Ridderinkhof et al. 2004; Botvinick et al. 2004; Barber and Carter 2005). In bilingual language control research specifically, ACC activity has been associated with monitoring *language conflict* (Abutalebi et al. 2008; Abutalebi et al. 2011). Such conflict has been typically operationalized in tasks such as picture naming paradigms in which the desired target language switches from trial to trial. It has been proposed that during such switching, conflict arises because two languages are competing for response selection and switching requires overriding the use of the current language (Van Heuven et al. 1998; De Groot et al. 2000; 2008).

Interestingly, our results show that ACC activation was not contingent on switching or overriding a previous response, as the preparation phases included both “switch” and “repeat” trials. Note that, however, our paradigm used a *mixed* design, with target language changing unpredictably from trial to trial. Thus, in these early and proficient bilinguals, language conflict was likely anticipated in our paradigm. In fact, our results suggest that the ACC may be engaged early to monitor the language in use at a global level under these language conflict conditions (Guo et al., 2011; Branzi et al., 2015). This interpretation is consistent with the results of Abutalebi et al. (2007), who showed that ACC activation was observed in bilingual language contexts, irrespective of whether the language of the trial is switched or repeated. With respect to preparatory processes more broadly, these results are also consistent with other findings in which ACC activation can be observed during cued preparation rather than during task execution (Luks, Simpson, Feiwell, & Miller, 2002; Fincham & Anderson, 2006; Sohn, Albert, Jung, Carter, & Anderson, 2007).

It is important to note that in our task, the classically defined ACC was *not* significantly involved in task execution (although more posterior portions of the mid-cingulate cortex were). The precise definition and location of the ACC ROI may explain why some previous bilingual language control paradigms implicate the ACC during task execution (Price, Green, & Von Studnitz, 1999; Abutalebi et al., 2007), while the current experiment does not. This also offers an alternate explanation of why the meta-analysis on bilingual language switching by Luk et al. (2012) did not find significant activation in the ACC across tasks. Taken together, these results highlight the importance of considering top-down preparatory processes in investigations of bilingual language control.

How do the neural networks involved in proactive control differ from those involved in bilingual language production? Our ROI analysis revealed that five of the nine regions that have been repeatedly implicated in bilingual language control had significantly different responses during task preparation and task execution, highlighting the importance of considering these phases separately. Specifically, the three left frontal (DLPFC, inferior frontal, and orbital frontal) regions along with pre-SMA were all significantly more active during task execution than during preparation, whereas the ACC was significantly more active during task preparation. The remaining four regions including the bilateral BG, left middle temporal, and right precentral ROIs, were equally active during preparation and execution.

These results, combined with those from the whole-brain analyses, partially overlap with those reported by Reverberi et al. (2015). First and foremost, both experiments implicate the precuneus and the left posterior temporal regions in Target Language Preparation (see Figure 3). Reverberi and colleagues propose that the precuneus activation is part of a broader "fronto-parietal control network responsible for directing selective attention" (Reverberi et al., 2015, p.8). It is notable that our preparation activation did include a broader fronto-parietal network, whereas theirs did not (see subsequent discussion of design differences). Interestingly, the precuneus has also been associated with thoughts of self (Northoff & Bermpohl, 2004; Cavanna & Trimble, 2006), internalized focus of attention (Mason et al., 2007), or the default mode network (Fox et al., 2005). Thus, it is possible that when bilingual individuals globally select or prepare to use a target language, some broader activation of different senses of "self" occurs. This is particularly interesting when considered in light of social-cognitive research on bicultural individuals, suggesting that different patterns of thinking and behaving can be primed by culture-specific scenarios (e.g., Benet-Martínez, Leu, Lee, & Morris, 2002).

One key difference between our results and those previously reported is that we found the medial prefrontal region (BA10) to be more involved in task preparation than task execution, whereas Reverberi et al. (2015) found this region to be implicated in task execution. This is not particularly troubling, since the contrasts reported herein differ in important ways from those reported by Reverberi. Specifically, Reverberi et al. (2015) contrasted activation in trials in which target language switched, from those in which target language repeated, looking separately at preparation and execution phases. In contrast, we looked at all trials in a mixed language design, and contrasted the preparation and execution phases directly. Therefore, it is possible that BA 10 is always active during preparation (especially in a mixed design as both experiments were), and is only active when conflict is high during execution of switch trials. This pattern would produce the results obtained in both experiments. Finally, it is important to note that Reverberi et al. (2015) found that the ACC and BG were particularly active during execution of trials in a non-dominant L2; however, our participants were early bilinguals with relatively balanced proficiency in both languages, and thus, these contrasts have little relevance for the current study.

How do the neural networks involved in global language selection differ from those involved in morpho-syntactic rule selection? In the current experiment, we investigated whether the type of control necessary for selecting a target language to speak in, and subsequently selecting the appropriate morpho-syntactic rule within that language differed. The difference between such global target selection and more local selection of rules and word forms within that language is central to the Adaptive Control Hypothesis described by Green and Abuatalebi (2013). Both types of preparation resulted in distributed activation in bilateral fronto-parietal networks, medial frontal regions, and the BG (see Table 6). Target language preparation, however, recruited more activation overall, with activation in the rostral prefrontal cortex, the ACC, and bilateral temporo-parietal regions being uniquely active. In contrast, there were no regions that were more active, or uniquely active during morpho-syntactic rule selection.

This pattern of results is consistent with the proposal made by Buchweitz and Prat (2013), that target language may be represented hierarchically in bilingual morpho-syntactic representations. However, as discussed in the previous sections, the fronto-parietal and medial networks observed during target language preparation are also consistent with a more general, top-down attention biasing network. Because target language information was always given at the beginning of a trial, it is possible that the greater activation in these regions simply reflects a strong response to the first cue about the upcoming trial. Future work investigating the processes involved in global language selection versus more specific lexical or morpho-syntactic processes may also want to account for order effects to control for this.

2.6. Conclusions and Caveats

Up until this point, we have focused on the response profiles of individual regions including the ACC, BG, and DLPFC across the various phases of our bilingual language control task. A mechanistic explanation of how these regions accomplish bilingual language control, however, requires a more complete understanding of how and when these regions interact and influence one another. In a recent dynamic causal modeling analysis, Becker and colleagues investigated such interactions by comparing models with different patterns of effective connectivity between the ACC, BG, and DLPFC in monolingual and bilingual individuals as they executed a non-linguistic RITL task (Becker et al., 2016). They found that the model in which the ACC exerted increased influence over both DLPFC and the BG during the condition that required the most control, novel task execution, best fit the data of both monolinguals and bilinguals. Additionally, they found differences in the strength and direction of these influences between monolinguals and bilinguals. The authors concluded that these differences are shaped by the increased demands for cognitive control in bilingual individuals. The fact that ACC activity was observed at the beginning of each trial, and preceded increased activation in the DLPFC may suggest a similar pattern of influence between these regions in the current experiment. To test this directly, future experiments should measure the effective connectivity between the language control regions discussed herein.

The interconnectivity of these regions can also be inferred from their co-reliance on dopamine pathways. For example, a recent experiment by Vaughn et al. (2016) found that variation in *DRD2*, a gene that relates to expression of dopamine receptors in the BG, predicts differences in neural activity in the inferior frontal gyrus and anterior cingulate cortex during linguistic and non-linguistic cognitive control tasks (Vaughn et al., 2016). In fact, Stocco and colleagues have proposed that bilinguals experience places extra demands in the dopamine gating system for target language selection and use, and that these demands may shape cognitive control more broadly (Stocco et al., 2010; Stocco & Prat, 2014). One interesting link between these two papers was recently reported by Hernandez and colleagues (Hernandez, Greene, Vaughn, Francis, & Grigorenko, 2015), who found that in the college population tested, different proportions of the *DRD2/ANKK1* polymorphism were observed between the bilinguals and monolinguals.

An additional limitation of this experiment is that to explore top-down language control mechanisms, we used symbolic cues to inform participants which language they would be using and which morpho-syntactic manipulation they would be performing. In doing so, we have arguably created a task that is more like a canonical cognitive control task than it is like a natural language task. In fact, the task is quite artificial, with no linguistic material being presented until the last phase of the task. Although this argument can be made of many controlled laboratory studies, subsequent research is needed to determine the extent to which the neural networks outlined herein are active in more naturalistic settings, such as when a bilingual views the face of an individual known to speak one language or another. In fact, one recent experiment on bilingual language switching showed that conditions in which natural contexts (faces) preceded a switching task, less ACC and PFC activity were observed than in conditions where more arbitrary cues (colored squares) preceded the task (Blanco-Elorrieta & Pylkkanen, 2017).

Despite these limitations, the results reported herein extend the body of research implicating general cognitive control regions in bilingual language control by showing that three core regions, the DLPFC, the BG, and the ACC, exhibit different patterns of activation across a bilingual morpho-syntactic rule production task. When viewed in light of existing research on both bilingual language control and cognitive control more broadly, we propose that the ACC may be involved in detecting language conflict at the earliest possible point, and using that information to trigger the fronto-striatal signal biasing system discussed by Stocco et al. (2014). The BG keep track of the target language and use this information to weigh competing signals, which converge on a structured network of rules for responding in the DLPFC.

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2.9. Supplementary Material

The experimental stimuli and data (including individual de-identified datasets, individual statistical analysis, group-level results, and the MATLAB and shell scripts to reproduce the analyses) are freely available on the Harvard Dataverse: doi:10.7910/DVN/W6WJVN.

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Chapter 3. Manuscript 2

Investigating Local and Global Control Mechanisms in Bilingual Grammatical Processing

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3.1. Abstract

Bilinguals employ both global and local control mechanisms to manage two co-activated languages that compete for selection, yet little is known about how they operate on morpho-syntactic information. The current study investigated bilingual language control mechanisms during a morpho-syntactic production task. Across two experiments, 48 early Spanish-English bilinguals completed Rapid Instructed Task Learning paradigms with priming in-item-recognition manipulations that investigated the extent to which parallel activation was observed across languages and across rules of the same type within a language. The results showed that it was more difficult to reject incorrect rules within the target language than to reject the correct rules in the non-target language, irrespective of the order in which this information was given in the task. These results converge with research on lexico-semantics and neuroimaging work suggesting that global control at the level of target language dominates bilingual morpho-syntactic selection processes.

3.2. Introduction

Speaking two languages fluently is not an easy task. Not only do bilinguals store two sets of word forms for communicating ideas, they also manage two sets of morpho-syntactic rules for manipulating them. Being bilingual is further complicated by the fact that when using one language, parallel memory activation occurs in the other language (Jacobs, Fricke, & Kroll, 2016; Kroll, Bobb, & Wodniecka, 2006; Marian & Spivey, 2003). Thus, to use two languages effectively, bilingual individuals must be able to select the contextually appropriate linguistic information from competing alternatives both within and across languages (see Buchweitz & Prat, 2013; Stocco, Yamasaki, Natalenko, & Prat, 2014). These processes are commonly referred to as “bilingual language control”.

Research on bilingual language control has shown that it is a multidimensional construct (Abutalebi & Green, 2016; Gollan & Goldrick, 2016; Green & Abutalebi, 2013; Hoversten, Brothers, Swaab, & Traxler, 2015; Yamasaki, Stocco, & Prat, 2018). For example, research has shown that bilingual language control is deployed on a global level (i.e., selecting which language to use), and at a local level (i.e., selecting which words and rules to use) (Abutalebi & Green, 2016; Seo, Stocco, & Prat, 2018; Green & Abutalebi, 2013). Two recent bilingual neuroimaging studies have shown that cues about which language (e.g., Spanish vs. English) will be used in the future enable bilinguals to deploy global control mechanisms proactively, preparing them to use the target language in advance (Reverberi et al., 2018; Seo et al,. 2018). Conversely, when faced with lexical items in absence of preparatory cues, research has shown that bilinguals quickly extract information about target language, and use this to modulate the degree of subsequent processing (Hoversten et al., 2015).

Despite these practiced global language control mechanisms, considerable research has shown that parallel memory activation occurs for local items across languages, even under conditions in which a single target language is being used for lengthy periods of time (see Kroll, Dussias, Bogulski, & Kroff, 2012 for review). The vast majority of this research has focused on lexico-semantic selection processes, and the predominant explanation for this has been that activation spreads automatically from word forms in one language to another through their shared semantic representations (Kroll & Stewart, 1994). Importantly, evidence from code switching and structural priming literature suggests that co-activation also occurs at the morpho-syntactic level (Hatzidaki, Branigan, & Pickering, 2011; Pickering & Ferreira, 2008). This research suggests that, morpho-syntactic rules may be organized in the bilingual mind according to their local functions (e.g., the order of direct and indirect objects in use of dative verbs), and that activation may spread from those local functions to the specific rules for accomplishing them in each language. Evidence supporting this type of organization can been seen in the code switching and structure priming literature, and in the second language learning literature suggesting that it is more difficult to acquire rules in a second language that do not already exist in your first language (i.e., Contrastive Analysis; James, 1980; Khalifa, 2018). Much less is known about the processes by which co-activation and selection occur in morpho-syntactic rule use, and what they may tell us about the nature of bilingual morpho-syntactic rule representation and language control more generally.

Despite the fact that lexico-semantic and morpho-syntactic information is highly integrated and interactive in memory systems (MacDonald, Pearlmutter, & Seidenberg, 1994), seminal studies have shown that morpho-syntactic knowledge can be queried independently from lexico-semantics by asking individuals to apply existing rules to novel stimuli (e.g., the Wug tests by Berko, 1958; Bialystok, Peets, & Moreno, 2014; Cuskley et al., 2015). This research demonstrates that the human brain is capable of extracting abstract grammatical rules from integrated representations (Berko, 1958). Thus, the current study employs a paradigm involving pseudoword manipulation to investigate morpho-syntactic rule application processes in Spanish-English bilingual individuals.

To investigate the nature of global and local bilingual language control, we adopted a Rapid Instructed Task Learning (RITL) paradigm. The RITL task was originally devised to assess non-linguistic, rule-based behaviors. As compared to traditional tasks, which typically employ a single set of rules applied to multiple stimuli, RITL tasks involve manipulations of task rules on a trial-by-trial basis, such that a different task is executed on each trial (Cole, Laurent, & Stocco, 2013). Such tasks have been increasingly used to study bilingual cognition in both linguistic (e.g., Seo at al., 2018) and non-linguistic contexts (e.g., Becker, Prat, & Stocco, 2016).

The majority of existing bilingual language control studies ensure that global control governs local control by presenting target language information either prior to or concurrent with the stimuli on which it will be applied (e.g., Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001). Thus, little is known about how control may operate differently under conditions in which local control (e.g., semantic or morphology processing) constraints precede global control (e.g., under dense code switching or dual language: Green & Abutalebi, 2013). In the current experiment, as in previous bilingual control RITL studies (Seo et al., 2018), the target language (global control) and morpho-syntactic rules (local control) were presented across subsequent rule phases. In the original study, global language selection preceded local rule selection; however, this order was manipulated across the two experiments reported herein.

Another limitation of the previous research on bilingual language control is that global and local influences are not readily separable, as global information about target language is typically available in the local items either in the cues (e.g., auditory cue 'Say' and 'Diga' for English and Spanish, respectively), the lexical items, or both (e.g., Hernandez et al., 2001). A feature of RITL tasks that circumvent this is that rules are presented *before* the stimuli on which they are to be applied, typically in an abstract, symbolic form. In the linguistic context, this allows for the unique opportunity to investigate proactive language control mechanisms in the absence of any involvement of bottom-up reactive control mechanisms that are deployable once target language has been extracted from the lexical items (e.g., Hoversten et al., 2015). The use of pseudo-verbs in the current experiment further removes the bottom-up influences of lexical stimuli even at the production phase.

Canonical RITL tasks also involve a subvocal production phase in which participants must generate the answer that would occur from applying the grammatical rule (e.g., target language = English, and rule = to pluralize) to the word or pseudoword (e.g., wug). Participants are instructed to press a button when they have generated an answer, and are then given a short period of time (typically one to two seconds) to decide whether a response probe (e.g., wug***s***) is correct or incorrect based on the answer they generated subvocally. Another novel manipulation of the current experiment is that the response probes were created such that a priming-in-item-recognition approach could be taken (Ratcliff & McKoon, 1978). In short, priming-in-item-recognition assumes that the speed and accuracy with which a probe can be recognized or rejected varies as a function of the strength of that item's memory trace. This approach has also been shown to be sensitive to individual differences in language skill (Prat, Long, & Baynes, 2007).

The current study investigates the effects of global and local control processes by examining behavior in the face of three types of response probe foils: (1) *Wrong Language* probes which consist of the correct morpho-syntactic rule in the non-target language (2) *Wrong Rule* probes which consist of an incorrect morpho-syntactic rule in the correct target language, and finally (3) *Wrong Both* probes which consist of an incorrect morpho-syntactic rule in the non-target language. Each of these three conditions is incorrect and requires a “NO” response. Previous research has shown that rejecting items that are active in memory is more difficult (as indexed by slower response times and poorer accuracy) than rejecting items that are not active in memory (Long & Baynes, 2002; Long, Baynes, & Prat, 2005; Prat et al., 2007). Hence, the extent to which participants are slower or less accurate to reject probes that are globally related (*Wrong Rule*) versus locally related (*Wrong Language*) will be taken to reflect their co-activation in memory.

In summary, with the novel modifications to a RITL paradigm employed across two experiments, the current research investigates the nature of global and local bilingual language control mechanisms with the goal of answering three interrelated questions: (1) Does co-activation of morpho-syntactic structures occur in the absence of bottom-up lexico-semantic information? (2) Are global and local selection mechanisms equally efficacious as evidenced by co-activation of interfering items from within and between languages? And (3) Does bilingual language control structure as manipulated by task order modulate the efficacy of global and local selection mechanisms?

3.2. Experiment 1 Method

Participants. Twenty-five early Spanish-English bilingual speakers (18 females, mean age = 19.16 years) who learned both languages before the age of 7 years were recruited for Experiment 1 using the University of Washington Psychology Subject Pool. All participants provided informed consent according to the guidelines of the Institutional Review Board at the University of Washington, and received course credit for their participation. Two participants were excluded based on poor performance on the Spanish Grammatical Proficiency Test (less than 50% accuracy). Data from the remaining 23 participants are reported herein. Participants' language profiles and proficiency scores are summarized in Table 1.

Table 1

Age of Acquisition of Second Language and Grammatical Proficiency Test Scores in Experiment 1

Age of Acquisition of L2		Spanish Grammatical Proficiency		English Grammatical Proficiency	
Mean (SEM)	Range	Mean (SEM)	Range	Mean (SEM)	Range
3.32 (0.42)	0 - 7 years	76.26% (2.42%)	50 – 96%	90% (1.63%)	50 – 92%

Note. Standard Error of the Mean (SEM) are in parentheses. The participants' second languages (L2) was typically English (*N* = 21). Four participants reported themselves as Spanish dominant speakers and 18 reported as English dominant speakers. Raw scores for Spanish Grammatical Proficiency Test and English Grammatical Proficiency Test are 50 and 20, respectively.

3.3. Materials

Paper and pencil tests. *English proficiency measure.* The English Grammatical Proficiency Test is a subtest of the "Examination for the Certificate of Proficiency in English" test developed at the University of Michigan (English Language Institute, 2006). It has previously been used in bilingual investigations as a measure of English proficiency (e.g., van Hell & Tanner, 2012) as it is sensitive to subtleties in English grammatical proficiency. The subtest consists of 20 multiple choice questions, and participants were given as much time as needed for completion.

Spanish proficiency measure. The Spanish Grammatical Proficiency test is a subtest of the standardized Spanish proficiency test issued from the ministry of Spanish education for Diplomas in Spanish as a Foreign Language (el Ministerio de Educación, 1988). This multiple choice, paper and pencil test has also been previously used to assess Spanish proficiency in bilingual research (e.g., Montrul & Bowles, 2009). The first 30 multiple choice questions are individual sentence completion tasks with one word missing. Participants select the correct word out of four options. The second 20 multiple choices questions are contextul, consisting of numbered gaps placed throughout a passage. Individuals are instructed to read the entire passage and then choose which of three options best completed each omission. Participants were given as much time as they needed to complete the test.

Bilingual language experience questionnaire. A modified version of the Language Experience and Proficiency Questionnaire (Marian, Blumenfeld, & Kaushanskaya, 2007) was used as a self-report measure of bilingual language experience and proficiency. The test asks participants to self-rate language comprehension, production, and reading proficiency. It also asks explicit questions about age of acquisition and background language experience. The modified version of this test has been used to characterize language experience in studies investigating individual differences in bilingual language experience (e.g., Yamasaki & Prat, 2014). This survey takes approximately 20-30 minutes.

Bilingual language switching questionnaire. Bilingual Language Switching Questionnaire is a self-reported assessment of bilingual language use and also includes questions investigating switching tendencies between languages (Rodriguez-Fornells, Kramer, Lorenzo-Seva, Festman, & Münte, 2012). An example of the questions is following: *I tend to switch language during a conversation (for example, I switch from English to [Second Language] or vice versa*). The answer choices are provided on a scale of 5 (i.e., 1. Never; 2. Very infrequently; 3. Occasionally; 4. Frequently; 5. Always). This survey takes approximately 5-10 minutes.

Stimuli. The pseudowords manipulated in the RITL task were generated through the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002). All pseudowords had orthographically existing onsets and bodies, ranged in length from 4-7 letters. To maximize the likelihood that our pseudowords would not be distinctively Spanish or English sounding, the word ending *-er* (common in both English and Spanish verbs) was added to the pseudowords. Each pseudoword was then tested using a norming study. Six early, proficient, Spanish-English bilingual speakers read and rated each word on a scale of 1 to 5 with 1 being ‘English sounding word’, 3 being ‘neutral’, and 5 being ‘Spanish sounding word’. Raters also confirmed that none of the words existed as real words in either Spanish or English. The final list was selected by choosing the 96 pseudowords with the most neutral ratings. The resulting stimulus list had a mean rating of 2.93, with a range of 2.17 and 4.3 standard deviation of 0.52. Sample pseudowords and their conjugations in each language are listed in Table 2.

Rapid Instructed Task Learning (RITL) paradigm. The RITL paradigm allows the experimenter to present instructions on how to conjugate a pseudoword in English or Spanish sequentially across three phases. The first "Prepare Target Language" phase instructed the participant to either use Spanish or English rules depending on the instruction given via a symbolic code (# or *). The specific symbol-language mapping was counterbalanced across participants. The second " Encode Rule" phase, involved the presentation of one of two codes indicating morpho-syntactic rules for manipulating verbs: past tense or present progressive tense. All rules were indicated with alphabetic symbols used in both languages ("A": past tense, "B": present progressive tense). Each type of rule and target language was presented an equal number of times across the experiment (24 Spanish past, 24 Spanish present progressive, 24 English past, and 24 English present progressive) in pseudorandom order. The third, "Execution" phase of the paradigm involved the presentation of a pseudoword which the participants were asked to manipulate according to the rules presented in the previous phases. In the final "Response Verification" phase of the experiment, a response verification probe was presented. Participants were asked to indicate whether the verb conjugation they had generated subvocally matched the response indicated on the screen. "YES" and "NO" responses corresponded to LEFT and RIGHT key presses. The precise hand-key mapping was counterbalanced across participants. Half of the response probes were correct, reflecting the answer that would be achieved if the correct language and correct rule were applied to the stimuli presented. The other half of the probes were incorrect, corresponding either to the application of the incorrect language but correct rule (16 items), incorrect rule but correct language (16 items), or both incorrect rule and incorrect language (16 items). An additional 16 "catch" items were added in which the appropriate verb ending occurred, but the spelling of the word root was incorrect. These item types were added so that participants would have to pay attention both to the word roots and to the word endings.

Response times were recorded for the first three phases, which were self-paced, but timed out after 2 seconds. Both accuracy and response times were recorded during the response verification probe, which timed out after 2 seconds to prevent participants from using the verification time to generate answers.

The complete RITL paradigm consisted of 96 trials which were presented in four blocks of 24 trials each. A schematic RITL trial presentation is depicted in Figure 1.

Table 2

Sample Stimuli for Spanish and English Trials

	English (#)		Spanish (*)	
	Stimulus	Response	Stimulus	Response
Past (A)	NESKER	NESKERED	NESKER	NESKIÓ
Present Progressive (B)	NESKER	NESKERING	NESKER	NESKIENDO

Note: Sample experimental symbols are in parentheses. Target language symbols: pound (#) and asterisk (*) were switched in version B presentation [i.e., English (*), Spanish (#)].

Procedure. All participants were tested individually. The experiment consisted of a battery of paper and pencil tests and computerized tests which took about 1 hour and 20 minutes to complete for each participant. The tests were presented in randomized orders.

Memory tests and practice tests. Participants received systematic memory training before participating in the the Rapid Instructed Task Learning (RITL) experiment. As is consistent in the field (Seo et al., 2018; Stocco & Prat, 2014) training was composed of two memory tasks (each written in Spanish and English) and a practice task. The order of the language used in presenting the memory tasks was counterbalanced across participants. In the memory test, participants learned the mapping between the symbols and their corresponding rules. The tasks presented four symbols and their corresponding rules in pairs (e.g., " # = English") three times in random order. After this learning phase, participants were asked to type the corresponding symbol when a rule was presented and to type the corresponding rule when a symbol was presented. The participants had to type the correct corresponding symbols and rules two times in a row without errors to complete the task. After the memory tasks, participants performed the practice task. The practice task consisting of 16 sample trials and was designed to acclimate the participants to the paradigm. Unlike the actual test, in the practice tests, accuracy and response time was provided after each trial to help the participants improve their performance. Each participant was given the opportunity to complete the practice task up to four times to prepare for the actual test.

Figure 1.

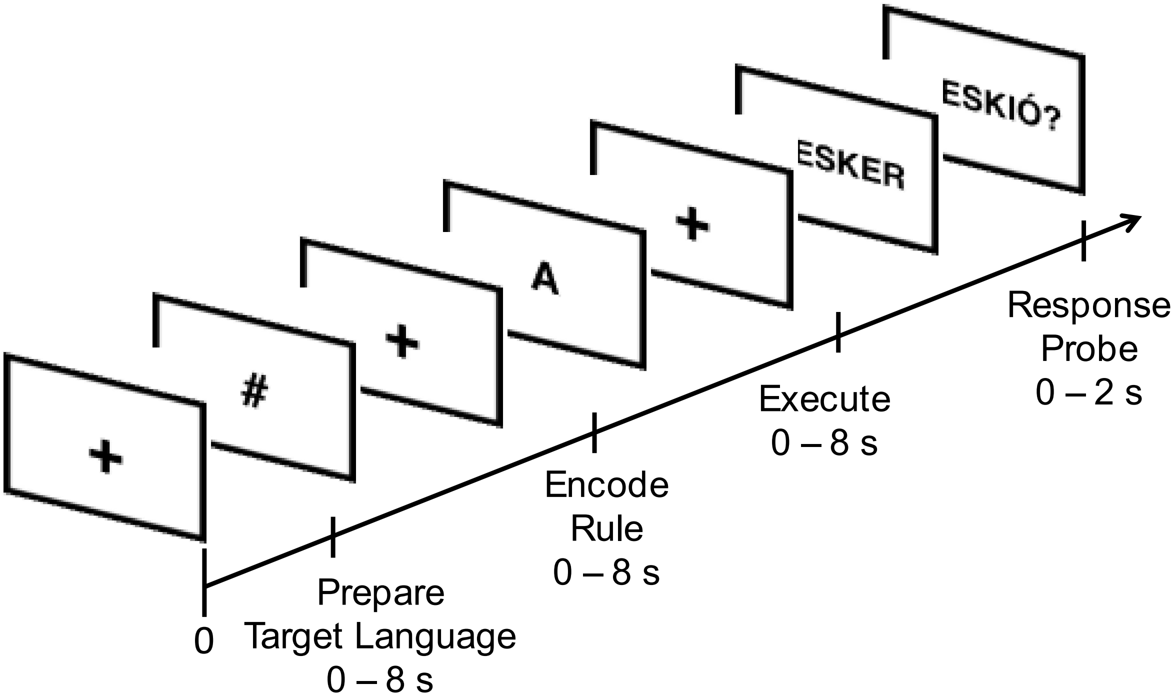

Figure 1. Schematic of a sample trial in Experiment 1 displaying Prepare Target Language, Encode Rule, Execute, and Response Probe phases.

Data analysis. Due to non-normally distributed outcomes in accuracy, an angular transformation was performed. Response times were analyzed for correct trials only. Responses that were more than three standard deviations from an individual participant's mean were removed. Outliers constituted approximately 0.996 % of the data. Mean accuracies and response times were analyzed using two separate one-way repeated measures ANOVAs to compare behavior across the three conditions of interest (i.e., *Wrong Language, Wrong Rule, Wrong Both*).

3.3. Experiment 1 Results

The mean accuracy rate for Experiment 1 collapsed conditions was high (*M* = 89.6%, *SEM* = 1.41%). The mean accuracies and response times by probe type are reported in Table 3. In addition, the mean response times for each phase are reported in Table 4.

Table 3

Mean Accuracy and Response Times by Types of Probes in Experiment 1

Exp 1.	Wrong Lang	Wrong Rule	Wrong Both	Wrong Root	Correct
Response Time (ms)	779. (26.3)	825. (41.2)	760. (21.3)	1011. (39.5)	859 (37.8)
Accuracy	1.51 (0.0326)	1.41 (0.0450)	1.53 (0.0210)	1.02 (0.0636)	1.28 (0.0322)

Note. Standard Errors of the Means are in parenthesis.

Table 4

Mean Response Times and Standard Errors of the Means in Each Phase

Exp 1.	Prepare Language	Encode Rule	Execute
Response Time (ms)	1445. (157)	1807. (153)	2748. (196)

Note. Standard Errors of the Means are in parenthesis. The maximum time for time out in each phase was 8 seconds.

Mauchly's test indicated that the assumption of sphericity had been violated in both the response time analysis and in the accuracy analysis. Therefore, the degrees of freedom for accuracies and response times were corrected using Greenhouse-Geisser estimates of sphericity. After applying the correction, the ANOVAs revealed that both response time ($F(1.31, 28.9) = 6.79$, $p = .009$) and accuracy ($F(1.55, 34.0) = 4.99$. $p = .0190$) differed significantly across probe type.

Pairwise follow-up comparisons showed that response times between *Wrong Language* and *Wrong Rule* conditions were different, with response times to *Wrong Rule* probes being significantly slower than response times to both *Wrong Languag*e probes ($p = .0110$), and to *Wrong Both* conditions ($p = .0120$). However, *Wrong Language* and *Wrong Both* conditions were not significantly different ($p = .248$).

Follow-up pairwise comparisons of the accuracy data revealed that *Wrong Rule* and *Wrong Both* conditions were significantly different, with accuracy being better in the *Wrong Both* condition ($p = .005$), but the difference between *Wrong Rule* and *Wrong Language con*ditions only approached significance ($p = .067$). *Wrong Language* and *Wrong Both* conditions were again not significantly different ($p = .411$).

Taken together, these results suggest that global control processes resulted in non-significant activation of the same morpho-syntactic rule structures across languages; whereas significant interference was observed for probes consisting of different morpho-syntactic rules within the target language (as indexed by slower response times and poorer accuracy). To illustrate, the magnitude of memory interference, in the two probe conditions of interest, operationalized as the difference in response times for *Wrong Language* - *Wrong Both* and *Wrong Rule* - *Wrong Both* are depicted in Figure 2.

Figure 2.

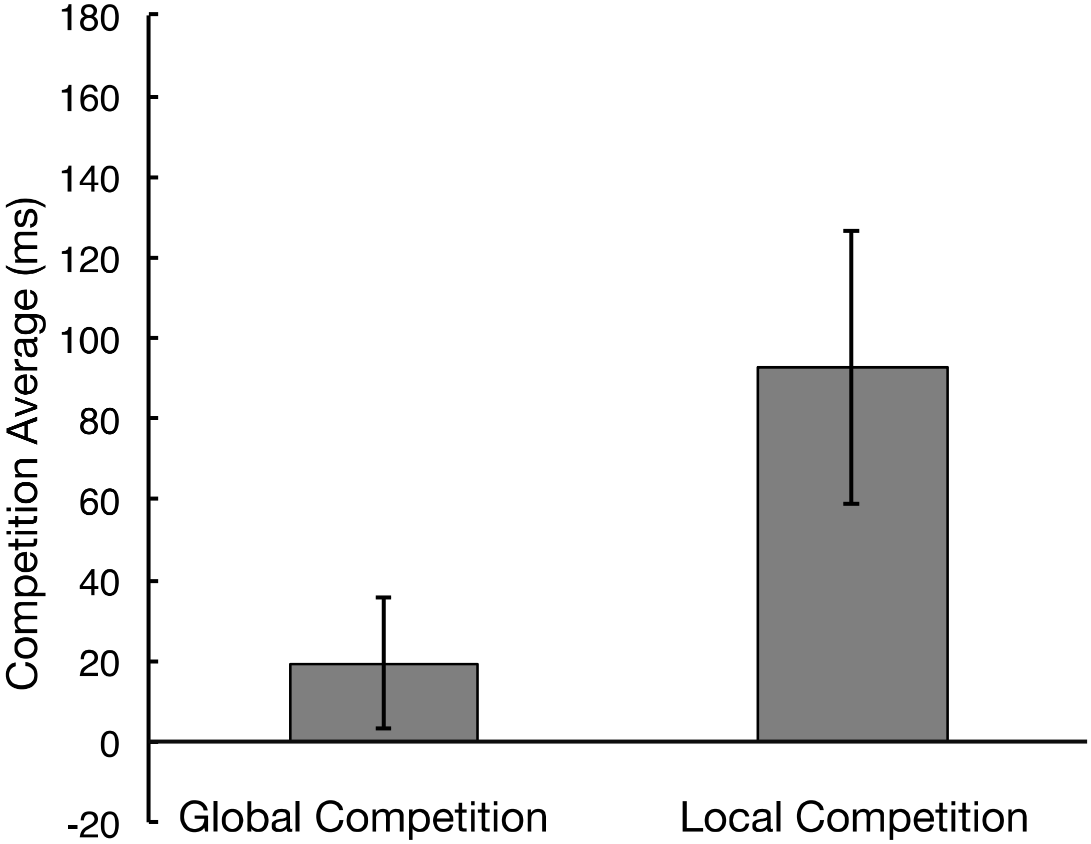

Figure 2. Global competition effect (left) and local competition effect (right) in Experiment 1. The global competition effect is the difference in reaction times between the *Wrong Language* condition and the *Wrong Both* condition. The local competition effect is the difference in reaction times between the *Wrong Rule* condition and *Wrong Both* condition. The error bars are the standard errors of the means.

3.4. Experiment 1 Discussion

To the best of our knowledge, this is the first experiment to investigate bilingual language control using an abstract, morpho-syntactic rule production paradigm. The implications of Experiment 1 are discussed herein, as outlined by the research questions posited in the introduction.

Does co-activation of morpho-syntactic structures occur in the absence of bottom-up lexico-semantic information? In the absence of lexico-semantic information, we observed that similar, verb conjugation rules within a language were more difficult to reject than were parallel rules across languages. The findings suggest that morpho-syntactic rule application results in a spreading memory activation to similar rules within a language. It is important to note that this finding was observed in the context of a highly artificial paradigm in which rules were given in absence of lexical items. Given this, these results suggest that at least in this condition, retrieval of rules within a language facilitates retrieval of other rules with similar goals within that language.

In the current study however, *Wrong Rule* foils only included other verb conjugation rules which were also used in the experiment on other trials. Future studies might investigate the extent to which similarity of the morpho-syntactic rules (e.g., pluralization or gender rules versus verb conjugation rules) drives co-activation within the language. Additionally, the extent to which a particular rule is task-relevant, even if it is not trial-relevant, should also be examined by including foils with rules that are never used in the task (e.g., future verb tense). It is possible that co-activation of alternate rules is driven by their use on previous trials, more so than by the use of a similar rule on the current trial. This possibility does not account for the fact that *Wrong*

Rule probes were more difficult to reject than *Wrong Language* probes, which were also used in different trials across tasks (see below for further discussion).

Are global and local selection mechanisms equally efficacious as evidenced by co-activation of interfering items from within and between languages? Results from Experiment 1 suggest that global control mechanisms are more strongly deployed during bilingual morpho-syntactic rule production than are local control mechanisms.

In the current study, the degree of effort to reject foils of varying types was taken to reflect the strength of activation of that particular rule in the memory trace. Thus, faster response times and marginally higher accuracy to *Wrong Language* probes than to *Wrong Rule* probes can be taken to reflect the fact that global control either strengthens rules associated with target language, or attenuates the signals associated with non target language. However, it is not clear to what extent the dominance of global control mechanisms in the current experiment are driven by the structure of the task. In Experiment 1, target language was the first instruction given in all trials. This manipulation may facilitate global control mechanisms in two ways: (1) by increasing the salience of target language selection, and (2) by providing more time for target language selection mechanisms to operate before the probe is presented. To control for the effects of task structure, a second experiment was run in which local, morpho-syntactic rules were provided before target language in the task instructions.

3.5. Experiment 2 Method

Participants. Thirty-seven Spanish-English bilingual speakers (mean age = 19.05 years; 27 females) were recruited for Experiment 2 using the University of Washington Psychology Subject Pool. All participants provided informed consent according to the guidelines of the Institutional Review Board at the University of Washington, and received course credit for their participation. Data from 6 participants were discarded because they did not meet age of acquisition (less than 7 years old, 3 subjects) or Spanish proficiency (greater than 50%, 3 subjects) requirements. Another 4 participants were excluded because of poor performance on the task (below 75% and data from two participants were excluded due to technical issues with hardware. Data from the remaining 25 participants are reported herein. Participants' language profiles and proficiency scores are summarized in Table 5.

Table 5

Age of Acquisition of Second Language and Grammatical Proficiency Test Scores in Experiment 2

Age of Acquisition of L2		Spanish Grammatical Proficiency		English Grammatical Proficiency	
Mean (SEM)	Range	Mean (SEM)	Range	Mean (SEM)	Range
4.36 (0.32)	1 - 7 years	75.36 % (2.17)	50 – 92 %	88.80% (1.98)	60 – 100 %

Note. Standard Error of the Mean (SEM) are in parentheses. The participants' second languages (L2) were either Spanish (N =1) or English. Three participants reported themselves as Spanish dominant speakers and 22 reported as English dominant speakers. Raw scores for Spanish Grammatical Proficiency Test and English Grammatical Proficiency Test are 50 and 20, respectively.

Materials and procedure. In Experiment 2, the Materials and Procedures used were identical to those used in Experiment 1, with the exception of the order of instructions presented in RITL paradigm. Specifically, the morpho-syntactic rule instruction was presented before the language rule.

Figure 3.

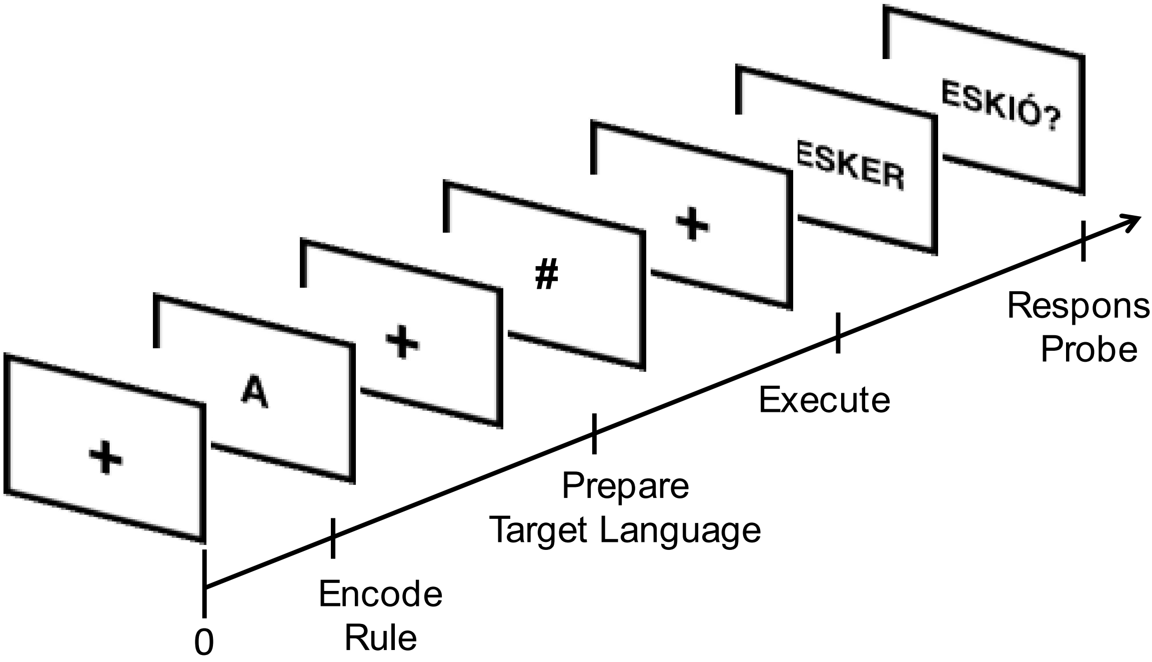

Figure 3. Schematic of a sample trial in Experiment 2 displaying Encode Rule, Prepare Target Language, Execute, and Response Probe phases. The order of Prepare Target Language and Encode Rule presentation was reversed in Experiment 2.

Data analysis. For the accuracy analysis, an angular transformation was ran to transform a binomial distribution into a normal distribution. Response times that were three standard deviations above from a participants' mean response time were removed. Outlier trials were 1.08 % of the data. Mean accuracies and response times were analyzed using separate one-way repeated measures ANOVAs and follow-up pairwise comparison tests were run on the three conditions of interest (i.e., *Wrong Language, Wrong Rule, Wrong Both*).

3.6. Experiment 2 Results

The mean accuracy rate for Experiment 2 was 90.8% with a standard error of the mean of 1.25%. Only correct trials were included for response time analyses. The mean accuracies and response times of the probes are reported in Table 6 and mean response time for each phase are reported in Table 7 separately.

Table 6

Mean Accuracy and Response Times by Types of Probes in Experiment 2

Exp 2.	Wrong Lang	Wrong Rule	Wrong Both	Wrong Root	Correct
Response Time (ms)	804. (27.7)	904. (37.3)	795. (27.1)	1005. (39.3)	838. (41.8)
Accuracy	1.50 (0.0255)	1.32 (0.0387)	1.50 (0.0310)	1.09 (0.0754)	1.32 (0.0304)

Note. Standard Errors of the Means are in parenthesis.

Table 7

Mean Response Times and Standard Errors of the Means in Each Phase

Exp 2.	Prepare Language	Encode Rule	Execute
Response Time (ms)	1515. (166)	1977. (212)	2813. (292)

Note. Standard Errors of the Means are in parenthesis. The maximum time for time out in each phase was 8 seconds.

Mean response times and accuracies were subsequently analyzed using one-way repeated measures ANOVAs to test whether there is significant difference across the means of the three critical conditions (i.e., *Wrong Language, Wrong Rule, Wrong Both*). Mauchly's test for sphericity indicated that an assumption for sphericity in response time was violated, but was not violated in response times. Therefore, the degrees of freedom for response times were corrected using Greenhouse-Geisser estimates of sphericity.

The mean response times were different across each condition ($F(1.42, 34.1) = 19.8$, $p < .001$) and pairwise comparisons showed that response times in *Wrong Language* were faster than *Wrong Rule* conditions ($p < .001$). Likewise, response times in *Wrong Both* were faster than *Wrong Rule* conditions ($p < .001$). However, *Wrong Language* and *Wrong Both* conditions were not significantly different ($p = .475$).

The mean accuracies were significantly different across the conditions ($F(2,48) = 10.891$. $p < .001$). Pairwise comparisons revealed that accuracies in *Wrong Language* as well as *Wrong Both* conditions were higher than in *Wrong Rule* conditions (both at $p = .001$), but a significant difference was not found between *Wrong Language* and *Wrong Both* ($p = .943$). Language competition was operationalized as the difference in response times between *Wrong Language* and *Wrong Both* conditions, and rule competition was operationalized as the difference between *Wrong Rule* and *Wrong Both* conditions. They are depicted in Figure 4.

Figure 4.

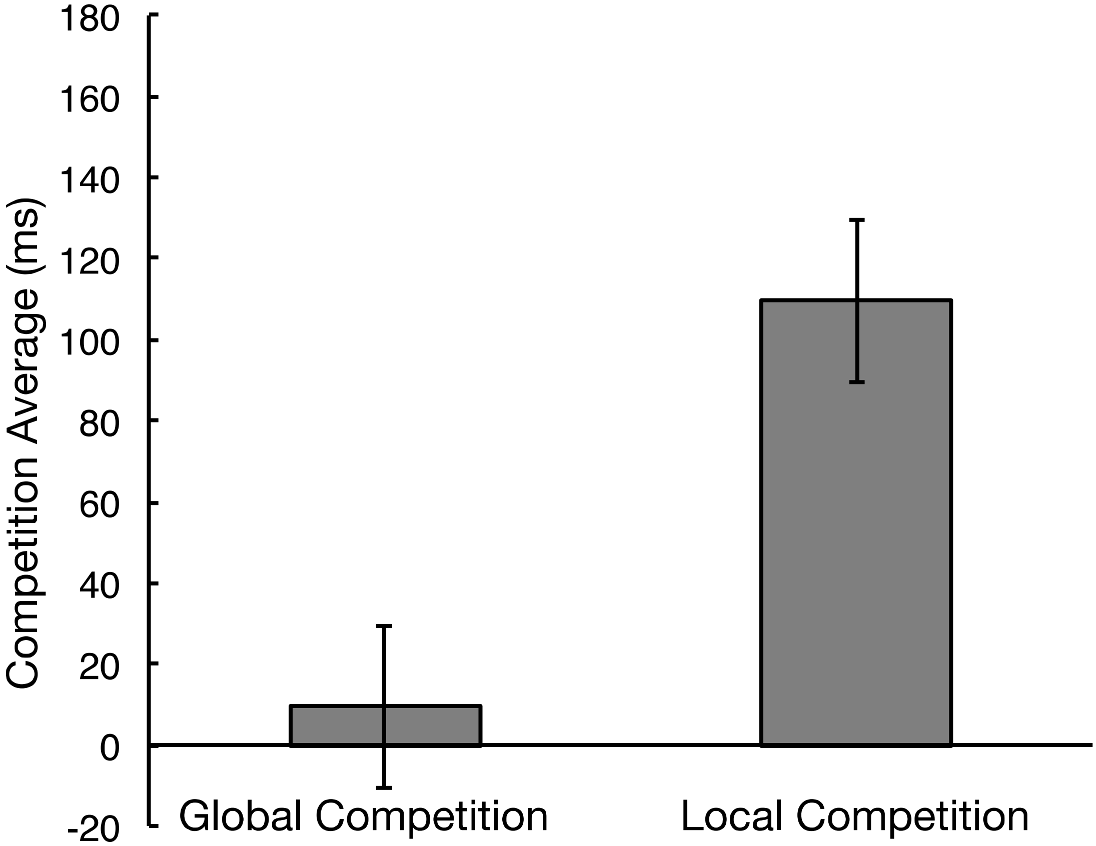

Figure 4. Global competition effect (left) and local competition effect (right) in Experiment 2. The global competition effect is the difference in reaction times between the *Wrong Language* condition and the *Wrong Both* condition. The local competition effect is the difference in reaction times between the *Wrong Rule* condition and *Wrong Both* condition. The error bars are the standard errors of the means.

3.7. Experiment 2 Discussion

The primary goal of Experiment 2 was to explore the answer to the third research question: *Does bilingual language control structure as manipulated by task order modulate the efficacy of global and local selection mechanisms?* In doing so, we were able to ascertain whether the dominance of global control mechanisms observed in Experiment 1 were driven by the order in which global and local selection criteria were presented in the task. Results from Experiment 2 largely replicate those from Experiment 1, with the exception that the difference between global and local selection mechanisms was slightly more prominent in Experiment 2, with accuracy effects that were marginally significant in Experiment 1 reaching significance in Experiment 2. This is particularly interesting given that Experiment 2 increased the salience of local control mechanisms. Taken together, the results from Experiments 1 and 2 provide evidence that control structure, as manipulated by rule order on a RITL task, does not modulate the efficiency of global versus local bilingual control mechanisms.

3.8. General Discussion

The current study aimed to investigate the role of global and local selection in bilingual morpho-syntactic processes. We found highly consistent results across two RITL experiments and in two different groups of bilingual participants suggesting that: (1) co-activation of morpho-syntactic rules within language occurred in the absence of lexico-semantic information, (2) that co-activation was found to be stronger within language than within-rules across languages, and (3) that this global selection bias occurred irrespective of the task structure. It is also worth noting that global language control preparation was always easier than local preparation, as indexed by faster response time to target language instructions than to rule instructions, despite the fact that there were only two options to select from in each phase (see Figure 5).

Figure 5.

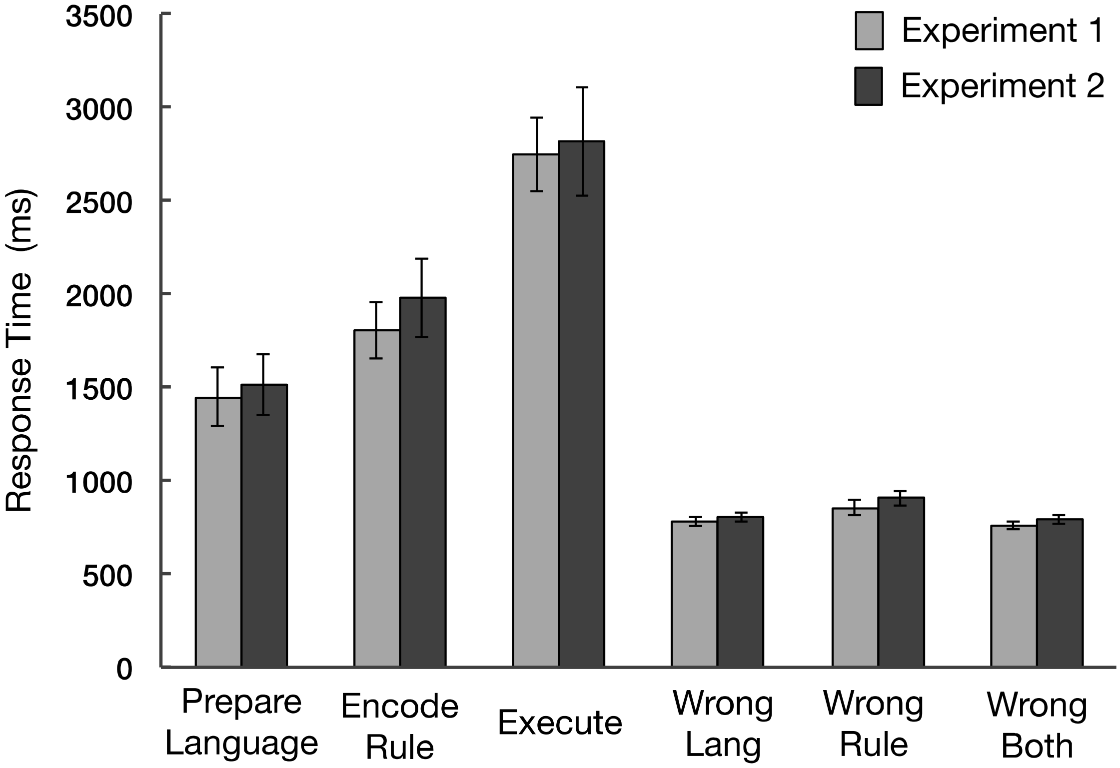

Figure 5. Response time comparison between Experiment 1 and Experiment 2.

These data are consistent with a recent neuroimaging study that compared patterns of activation when bilingual individuals deployed global versus local control mechanisms in a similar RITL task employing morpho-syntactic manipulations. Specifically, Seo and colleagues (2018) found that more distributed activation was observed when bilinguals were given information about global demands (target language) than when they were given information about local demands (rule selection). This activation was most notably observed in the anterior cingulate cortex, which is largely implicated in performance and conflict monitoring (Abutalebi et al., 2007; Abutalebi et al., 2011; Barber & Carter, 2004; Badgaiyan & Posner, 1998; Botvinick, Cohen, & Carter, 2004; Carter et al., 1998; Seo et al., 2018). The data from Seo et al., (2018) can be used to elaborate the results of the current study, as neuroimaging data allow us to make inferences about the nature of processes that are deployed during the control and production phases of this task that do not result in overt behaviors.

Results of the current study also extend the results from Seo et al., (2018) in critical ways. First, in the neuroimaging investigation, rule order was never manipulated. Thus it was unclear whether the increased activation in anterior cingulate was associated with global language control specifically, or with some parameter setting process associated with the first rule in the task being given. Although we cannot fully discount the latter option due to no imaging data being collected in these experiments, the dominance of language control selection mechanisms across both tasks lends credibility to the hypothesis that conflict is being monitored primarily at the global, target language selection level. Additionally, the combination of the pseudo-verb use and item recognition components of the current experiment allowed us to investigate the contents of participants' memories in a way that has not been previously done. Thus, the results obtained from the current experiments in combination with the previous neuroimaging research provide compelling evidence both about the neurocognitive mechanisms deployed during global and local bilingual language control, and about the outputs or effects of these mechanisms on the bilingual mind. Taken together, this body of work offers key insights about dissociable global and local bilingual language control mechanisms.

One novel finding across the current experiments is that global and local control mechanisms did not appear to change as a function of task structure. Because of the artificial nature of these tasks, however, it is unclear whether our manipulations relate to the differing demands of bilingual language use as outlined in the adaptive control hypothesis (Abutalebi & Green, 2016; Green & Abutalebi, 2013). Specifically, the adaptive control hypothesis posits that different language control mechanisms arise as a function of varying linguistic environments. For instance, much less (or no) global language control would be recruited in dense code switching environments as opposed to in single language circumstances (Green & Abutalebi, 2013). In the current experiment, bilingual individuals were always required to maintain a single language across an individual trial, but languages were mixed from trial to trial at random. Future research may want to create larger variations in local versus global demands, such that language stays constant across blocks, or varies even within a trial.

Another possible explanation for the pattern of results observed is that irrespective of the task structure provided, the predominance of global control mechanisms displayed by bilinguals in our experiments reflects the similar canonical language environments of this rather homogeneous group of bilinguals. Specifically, it is likely that Spanish-English bilinguals in Seattle spend a considerable amount of time speaking in single language (English) environments. To explore this possibility, we computed a post-hoc exploratory correlation examining the relative strength of local and global control mechanisms as a function of participants' responses to the following question *"I tend to switch language during a conversation"* on a scale of 1 (never) to 5 (always). Results suggested a modest correlation between self-reported switching behaviors and global dominance [*r*(46) = .339, *p* = .0182], suggesting that frequent switchers had larger differences in accuracy between *Wrong Language* and *Wrong Rule* probes than did infrequent switchers. We see this as another interesting avenue for future research.

In summary, results from the current experiment converge with previous research suggesting that global and local bilingual control mechanisms are dissociable in both brain and behavior, adding that global, target language selection mechanisms are deployed during morpho-syntactic rule production tasks. The current research adds to a growing body of work demonstrating the utility of RITL tasks in studying linguistic phenomena, as they allow the experimental separation of highly complex and interactive processes that occur during natural language use. As in previous research however, we acknowledge that in separating these phenomena in artificial tasks, we may be fundamentally changing the way they operate in natural language. Thus, converging work using more naturalistic paradigms is also needed.

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Chapter 4. Manuscript 3

Proactive and Reactive Language Control in the Bilingual Brain

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4.1. Abstract

The current experiment investigated bilingual language control within the dual mechanism framework. Using an fMRI morphosyntactic rule production task that manipulated presence or absence of target language cues, we investigate the neural mechanisms associated with engaging proactive control to bias a global target language, and compared them to those engaged when conflict between languages was experienced reactively. Patterns of activation across nine regions of interest (ROIs) were investigated in seventeen early Spanish-English bilingual speakers. Individual differences analyses showed that proactive control in the basal ganglia (informative > non-informative trial activation during preparation) was correlated with cue sensitivity in left DLPFC, left IFG, and right precentral ROIs. In contrast, reactive control in the anterior cingulate was correlated with conflict sensitivity (non-informative > informative activation during execution) in the Pre-Supplementary motor and left orbital frontal ROIs. No ROI was differentially activated as a function of languages switching versus repeating across trials.

Highlights.

- Informative target language cues resulted in faster morpho-syntactic rule execution and decreased activation in DLPFC and Pre-SMA in bilingual individuals.
- Cuing effects in bilateral caudate and bilateral prefrontal ROIs were correlated across individuals.
- Conflict sensitivity during non-cued task execution in the ACC, Pre-SMA, and left orbital frontal ROIs were correlated across individuals.

Keywords.

Bilingual Language Control, Proactive Control, Cognitive Control, Anterior cingulate cortex

Basal Ganglia, Dorsolateral prefrontal cortex

The average speaker knows more than one language (Bialystok, Craik & Luk, 2012; Shin & Kominski, 2010), and an increasing amount of research has been dedicated to understanding the particular neurocognitive demands associated with managing multiple languages (Abutalebi & Green, 2016; Bialystok et al., 2012; Blanco-Elorrieta, & Pylkkänen, 2018; Buchweitz & Prat 2001). These demands arise because relevant information becomes activated across languages, creating additional requirements for selection and interference management processes (Bialystok, 2001; Costa, Miozzo, & Caramazza, 1999; Kroll, Bobb, & Wodniecka, 2006; Kroll & Stewart, 1994; Van Heuven, Dijkstra, & Grainger, 1998).

Research on bilingual language control has increasingly highlighted its dynamic and adaptive nature. For instance, bilinguals must deploy control mechanisms across different levels of selection such as globally biasing the availability of one language over another versus selecting among local competitors at the morphosyntactic and lexico-semantic levels (Abutalebi, & Green, 2016). The former is unique to bilingual language control and the latter process is shared between bilinguals and monolinguals. Additionally, bilingual language control processes can be deployed ahead of time, under conditions in which an individual knows which language he or she will need to use in advance, or “on the fly” when linguistic cues are not provided (Abutalebi & Green 2016; Green & Abutalebi, 2013).

One of the most influential models of how such bilingual language control is accomplished is the adaptive control hypothesis (Green & Abutalebi, 2013), which posits that bilinguals deploy a network of regions more generally involved in action selection and cognitive control to manage competition between languages. One of the central tenets of this hypothesis is that bilingual language control, like cognitive control more generally, changes according to the demands of the linguistic environment a bilingual is speaking in. Specifically, Abutalebi and colleagues describe eight control processes including goal maintenance, conflict monitoring, interference suppression, salient cue detection, selective response inhibition, task engagement, task disengagement, and opportunistic planning, and describe the linguistic contexts under which the eight control processes would most likely be engaged (2013). Green and Abutalebi also propose a network of regions involved in these processes including the anterior cingulate cortex (ACC) and Pre-supplementary motor area (Pre-SMA) for conflict monitoring and speech control, the left inferior frontal (IFG) and dorsolateral prefrontal cortex (DLPFC) for interference suppression, bilateral parietal lobes for goal maintenance pertaining to the language in use, right inferior frontal cortex and thalamus for salient cue detection, and response inhibition, and the left caudate nucleus for executing language switching (Abutalebi & Green 2016; Green & Abutalebi, 2013).

Although this adaptive control hypothesis accounts for many phenomena described in the bilingual language control literature, a few questions remain. First, a meta-analysis of bilingual language control research did not find consistent involvement of the ACC, the parietal cortices nor the thalamus (Luk, Green, Abutalebi, & Grady, 2012). The meta-analysis did find reliable clusters of activation in the left IFG, DLPFC, caudate nucleus, and medial ACC/Pre-SMA regions as well as in the right precentral gyrus, which overlap with the adaptive control regions. The meta-analysis also revealed reliable involvement of the left inferior-orbital frontal region (BA47), the right caudate nucleus, and bilateral temporal regions, which are not included in the adaptive control hypothesis. Thus, some open questions remain about the nature of contributions of these regions to bilingual language control.

Additionally, some of the proposed neurocognitive relationships in the adaptive control hypothesis differ from those reported in the general cognitive control literature. For example, Braver's dual mechanism framework (Braver, Gray, & Burgess, 2007) proposes two "modes" in which cognitive control processes might be deployed, with high relevance and overlap to the bilingual language control processes outlined in the adaptive control hypothesis (Green & Abutalebi, 2013). Specifically, according to the dual mechanism framework, **proactive control** is defined as a form of "early" selection or attention biasing process, during which information about the task at hand is maintained in working memory and used to optimally guide subsequent perception and action systems (Braver et al., 2007). **Reactive control**, on the other hand, is a control mode recruited on the fly as a "late" correction, when a high-conflict event is detected. According to Braver and colleagues (2007), proactive control requires goal maintenance, which is underpinned by early and sustained activation of the lateral prefrontal cortices, accompanied by dopaminergic responses to contextual (salient) cues. Hence, the dual mechanism framework and adaptive control hypothesis make different predictions about the roles of lateral prefrontal, parietal, and basal ganglia regions during proactive control. Furthermore, Braver (2012) discusses reactive control as being underpinned by transient lateral prefrontal activation triggered either by ACC conflict monitoring system or by a temporal associative memory region. This provides an explanation for the role of the left medial temporal region uncovered by the meta-analysis, and shows convergence between dual mechanisms and adaptive control in terms of a role of the ACC in conflict monitoring.

Integrating these perspectives is important, as an increasing body of behavioral and EEG research on bilingual language control has demonstrated that bilinguals deploy proactive control mechanism when cues (either from the environment or the experimental paradigm) provide them with information about which language they will be speaking in (Bonfieni, Branigan, Pickering, & Sorace, 2019, Grainger, Declerck, & Marzouki, 2017; Martin, Molnar, & Carreiras, 2016;

Woumans et al., 2015). For instance, the impact of target language cueing was recently studied by Grainger et al. (2017) who showed that French-English bilinguals' performance on a bilingual lexical decision task was significantly facilitated when an image of a French or British flag preceded the word or pseudoword by 50 ms. Importantly, this facilitation was only observed when the flag and language matched (e.g., a British flag preceded an English word). Related evidence was provided by Woumans et al., (2015) who trained Spanish-Catalan and Dutch-French bilingual participants to associate specific interlocutor's faces with predictable speaking behaviors. Critically for the experiment, six faces always used one of the language the participants use and the other six faces used the other language the participants use. In the test trials, a 50% of time, the familiar faces use the language they used in the training period, and the rest, they used the other language. Bilingual participants completed a verb generation study in which the bilingual participants were asked to come up with a verb that is related to a noun suggested. When a trial was preceded (2000 ms) by a congruent face (i.e., Spoken language matches between training and test trials) bilinguals produced verbs significantly faster than when the same trial was preceded by a bilingual face cue. Together, both studies demonstrated that bilinguals use proactive cues to facilitate language control by showing that *informative* cues resulted in shorter response times during various language comprehension and production processes.

To date, a small number of experiments have investigated the neurobiology of such proactive control in bilinguals. In a recent experiment, Seo and colleagues (2018) investigated patterns of activation in nine ROIs previously identified by either Luk et al. (2012) meta analysis, or by the adaptive control hypothesis (2013) in a morpho-syntactic rule execution paradigm. To investigate the nature of proactive global and local language selection processes, Seo and colleagues (2018) employed a Rapid Instructed Task Learning (RITL) paradigm. RITL paradigm was developed to study cognitive flexibility, particularly as it pertains to executing rule-based behaviors (Cole, Laurent, & Stocco, 2013; Stocco, Lebiere, O'reilly, & Anderson, 2012). A critical feature of the RITL paradigm is that the conditions for completing each trial change across the paradigm, which allows one to study dynamic reconfiguring of control structures such as those described in the adaptive control hypothesis. Because the rules are presented before the stimuli on which the rules need to be applied, one can estimate the neural basis of proactive, top-down control structures separately from those involved in more reactive, task execution processes. Although non-linguistic RITL paradigms have previously been employed to investigate cognitive control structures in monolinguals and bilinguals (Becker, Prat, & Stocco, 2016; Stocco & Prat, 2014), Seo, Stocco, & Prat (2018) was the first to use a RITL paradigm to investigate bilingual language control. To do so, Seo and colleagues (2018) presented task rules in two phases: a target language phase presented first, and a grammatical rule phase presented second, and then presented lexical stimuli which the bilingual needed to modify according to the target language and rule instruction provided.

The results of the experiment showed three distinct patterns of activation across task phases: global language preparation recruited a distributed network including the ACC/Pre-SMA, left lateral prefrontal cortex, right precentral gyrus, bilateral caudate nuclei, and bilateral temporo-parietal regions. More focal patterns of activation were observed during local, rule-preparation processes, including the left inferior and middle frontal regions, left parietal regions, the right precentral gyrus, and bilateral caudate nuclei. Region of interest analyses showed that the ACC was primarily activated during top-down global language preparation, which is somewhat inconsistent with both Braver et al. dual framework model and the adaptive control hypothesis (2007). In contrast, activation in three left lateral ROIs as well as in the Pre-SMA increased across task phases and was highest during execution of the morphosyntactic rule. Activity in bilateral caudate nuclei, the middle temporal lobe and the right precentral gyrus remained active across task phases.

One limitation of using this research to adjudicate between the dual mechanisms and adaptive control accounts is that according to Braver (2012), individuals vary in the extent to which they use cues proactively to prepare for subsequent conflict. Because Seo and colleagues (2018) did not have any non-informative cued trials to use as a baseline, and because target language information could eventually be gleaned when the words were given during task execution, the extent to which an individual employed language cues to prepare proactively could not be estimated. Another limitation of the previous study is that the cues used to indicate target language and rule instructions were highly arbitrary (numbers and symbols) and participants had to be trained to retrieve the associated rules ahead of time. Thus, the involvement of lateral prefrontal and temporo-parietal regions in the previous study may reflect artificial memory demands of the task, rather than any particular process related to bilingual language control.

The current study aims to circumvent the limitations of existing research in multiple ways. First, like Woumans et al. (2015) but unlike Seo et al. (2018) the current study includes both conditions in which trials are preceded by informative language cues and conditions in which trials are preceded by non-informative cues, and does so in an fMRI scanning environment. In addition, the absence of non-cued trials in the original experiment by Seo et al. (2018) prevented the researchers from demonstrating the expected behavioral effects of proactive control, namely, that execution will be facilitated based on the top-down selection of target-language-relevant information during execution. In fact, a subsequent study by Seo and Prat (under review) reported the results of two behavioral studies using item-priming-in-recognition to show that when bilinguals receive target language information, bilinguals may use this information to inhibit information from non-target-language grammatical rule sets. Consistent with this, we expected that trials with proactive language cues will be executed more rapidly than will trials without these cues. Another limitation of previous research by Seo et al. (2018) was that the degree to which target language switched from one trial to the next was not manipulated. As regions such as the ACC, which were highly activated during preparation in the original experiment, Pre-SMA, and basal ganglia are believed to be sensitive to conflict or language switching (Abutalebi et al., 2007; Botvinick, 2007; Rushworth, Hadland, Gaffan, & Passingham, 2003; Wang, Xue, Chen, Xue, & Dong, 2007), the current experiment compared preparatory activation over trials in which the target language switched from the previous trial to those in which it repeated. Also, the current replaced arbitrary, memory demanding cues with cues that have existing semantic associations with the rules to-be-executed. Specifically, national flags were used to indicate which language a trial would occur in (Spanish or English) and stick figures of one or two persons were used to indicate which verb form (third person singular or plural) to use in the morphosyntactic rule execution experiment.

Finally, one major limitation of the existing research on target language cueing is that it fails to account for individual differences. Although the presentation of a preparatory language cue allows an individual to use proactive control mechanisms to prepare to use a given language, participants are not required to do so. It is because as target language information in three of the four experiments discussed was also provided during task execution, when the stimuli were presented in the to-be-used target language. In fact, Braver's dual mechanism framework discusses both the conditions in which proactive control may be deployed and the individual differences that may mediate whether an individual chooses to do so (2012). Thus, the current study will also compare patterns of activation across preparation and execution phases, as well as response times during informative cued and non-informative cued trials at the individual level to investigate the neurocognitive basis of proactive bilingual language control mechanisms.

4.2. Method

Participants. Seventeen, right-handed Spanish-English bilinguals were paid for participation in the current study (8 females, aged 18-21 years). Participants were required to be highly proficient in both languages, as assessed through grammatical proficiency tests, and to have learned both languages before the age of seven. Participants were healthy, with no history of developmental or neurological disorders. All participants provided informed consent, consistent with the protocols approved by the University of Washington's Institutional Review Board. Participants' language profile information is summarized in Table 1.

Table 1.

Language Profile of Bilingual Participants

L2 Age of Acquisition		Spanish Grammatical Proficiency		English Grammatical Proficiency	
Mean	Range	Mean	Range	Mean	Range
4.3 (.43)	0 -5	76.94 (2.98)	50 - 94	92.94 (1.66)	80 - 100

Note. The units for each variable are are in years, Spanish grammatical proficiency in percentage (%), and English grammatical proficiency in percentage (%). Standard errors of the means are in the parentheses. For all participants, their second languages (L2) were English. Raw scores for Spanish grammatical proficiency and English grammatical proficiency are 50 and 20, respectively.

Materials. ***Rapid Instructed Task Learning (RITL) paradigm.*** The RITL paradigm used in the current experiment consisted of 48 total trials, 24 in English and 24 in Spanish. Each trial consisted of one of two morpho-syntactic verb manipulations; third person singular present conjugation and third person plural present conjugation. Each of which occurred on 50% of the trials. The total of 48 trials were divided into six blocks of eight trials each, and each block contained equal proportions of English and Spanish trials and singular and plural verb conjugations. The trials were presented in pseudo randomized order, such that from trial to trial, languages switched 50 percent of the time (21 trials) and repeated 50 percent of the time (21 trials), with the remaining 6 trials being the first trial in each block. Across blocks, proactive and reactive control were manipulated. Participants were informed at the beginning of each block whether the trials within it would be cued-language (with target language presented in advance) or non-cued (with target language *not* presented in advance). The resulting three proactive, cued-language blocks (A) and three reactive, non-cued language blocks (B) were presented either in ABBAAB or in BAABBA order, counterbalanced across participants.

Consistent with previous research on bilingual language control (Seo et al., 2018; Seo & Prat, under review) each trial involved the presentation of information across four phases. The first "Prepare Target Language" phase consisted of two flags: the national flag of the Great Britain as a cue for English, and the national flag of Spain, as a cue for Spanish. During the “Prepare Target Language” phase in the informative cued language blocks, one of the two flags was presented in color to indicate which language would be used in the upcoming trial. In the non-informative cued blocks, both national flags were presented in grey color, indicating that it was unknown which language would be in use in that trial. The second "Select Rule" phase of the task involved the presentation of one of two morpho-syntactic verb conjugation rules: third-person *singular* present tense or third person *plural* present tense). Singular present tense was indicated with a single stick figure, and plural present tense was indicated with two stick figures. The third "Execution" phase of the experiment involved the presentation of an infinitive verb in either English or Spanish. During the non-informative cued language blocks, this was the first indication participants had about what language to execute the trial in. During informative cued blocks, the language of the verb appeared in Execution always matched the language of the cue. Finally a “Response Verification Probe” was presented. Half of the response probes were correct (matched the language and rule conjugation indicated by the trial) and the other half were false, consisting equally frequently of errors in target language, in conjugation rule, or in both target language and rule. A schematic of the paradigm is depicted in Figure 1.

Figure 1.

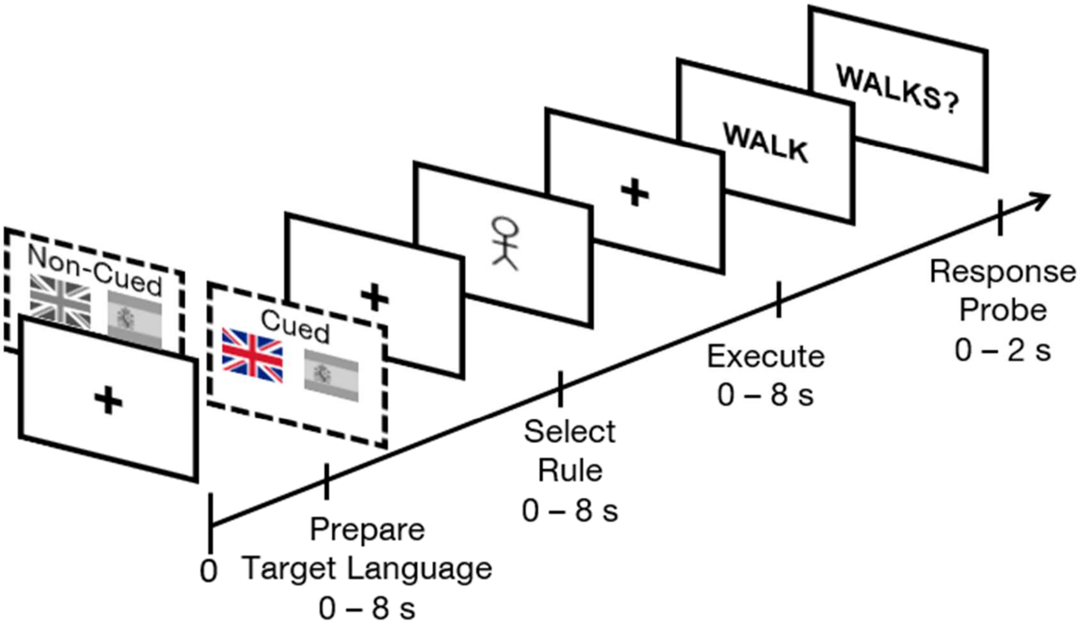


Figure 1. Schematic of sample informative cued and non-informative cued trials in Rapid Instructed Task Learning (RITL) displaying Preparing Target Language, Select Rule, Execute and Response Probe phases. In informative cued trials, the one of the two Great Britain and Spanish national flags is colored indicating a target language while in non-informative cued trials, both flags are in grey.

All verbs selected were regular in conjugation in both Spanish and English. The average frequency in rank was 1125.25 (top 0.004%) with a standard deviation of 1130.74 (cf. median is 639 with minimum 73, and maximum 4265) (Wiktionary, 2018). Translational equivalents were presented across lists and across participants, not within lists. Sample stimuli for Spanish and English trials are listed in Table 2.

Table 2

Sample Stimuli for Spanish and English Trials

Grammatical Rule	English		Spanish	
	Stimulus	Response	Stimulus	Response
Singular Present	TO WALK	WALKS	CAMINAR	CAMINA
Plural Present		WALK		CAMINAN

Handedness questionnaire. Participants' handedness was assessed using the Oldfield Handedness Inventory (Oldfield, 1971). In the survey, participants were asked to rate whether they used left, right or both hands when they do 10 tasks. Handedness is then calculated using the ratio between right greater than left handed responses over right plus left handed responses.

English proficiency measure. Participants' English proficiency was measured using the English Grammatical Proficiency Test. The test is a subtest of the "Examination for the Certificate of Proficiency in English" developed at the University of Michigan (English Language Institute, 2006). Participants were asked to answer 20 multiple choice English grammatical questions and were allowed to spend as much as time as needed to do so.

Spanish proficiency measure. Participants' Spanish proficiency was assessed with the Spanish Grammatical Proficiency test. This test is a subtest of standardized Spanish grammar proficiency test issued from ministry of Spanish education for Diplomas in Spanish as a Foreign Language (el Ministerio de Educación, 1988). The 20 multiple choice questions and 20 fill-in the blank questions were provided and participants were given as much time as they needed to.

Bilingual language experience questionnaire. Participants' bilingual language experience and proficiency were asked through a modified version of the Language Experience and Proficiency Questionnaire (LEAP-Q: Marian, Blumenfeld, & Kaushanskaya, 2007). The test asks participants to self-rate their language comprehension, production, and reading proficiency, and also asks explicit questions about their background of the language experience. This test has previously been used to investigate individual differences in bilingual language profile and experience (e.g., Seo et al., 2018).

Procedure. ***Behavioral testing session***. Behavioral testing was completed first, with the fMRI session following within two days. The behavioral session included completion of the Edinburgh Handedness Inventory (Oldfield, 1971) and LEAP-Q test (Marian et al., 2007). Following completion of these tasks, participants completed a RITL practice run. Each participant completed 12 practice RITL trials composed of 2 blocks: informative cued language block (6 trials) and non-informative cued block (6 trials). In the practice trials, unlike the test in fMRI, participants were able to learn how they were performing with explicit feedback on response times and accuracy. Practice runs ensured that participants understood the task and could successfully perform it in the scanner. The total behavioral testing session took approximately one hour.

fMRI data Acquisition. Data were collected using a 3.0 T Philips Achieva scanner at the Integrative Brain Imaging Center operated by the University of Washington. The study was performed with a gradient echo planar pulse sequence with TR = 2000 milliseconds, TE = 25 milliseconds, a 79° flip angle and field of view = 240 mm x 240 mm. Thirty-eight oblique-axial slices were imaged in an ascending order, and each slice was 3-mm thick aligned to the anterior commissure-posterior commissure with no gap. The acquisition matrix was 80 × 80 with 3 × 3 × 3 mm voxels. This typically constitutes full coverage of the cerebrum. In the neuroimaging analysis procedures, any predefined region of interest that was not completely covered in all participants was excluded.

RITL paradigm presentation. As is typical of RITL paradigms, presentation of the first three phases were self-paced with the experimenter-paced Response Verification Probe phases. Participants were asked to press a button as soon as they encoded instructions during the Prepare Target Language and Select Rule phases. During the Execute phase, participants pressed a button after they had conjugated the verb presented according to the instructions previously specified. If a button press was absent within 8 seconds during Prepare Target Language, Select Rule, or Execute phases, the trial "timed out" and automatically proceeded to the next phase. As is typical with RITL paradigms, the Response Verification Probe was only for 2000 milliseconds to encourage participants to generate the correct answer during the Execute phase. During the two seconds in Response Verification Probe, participants responded YES for correct or NO for incorrect answers. The button box with the hand corresponding to the position of the YES or NO labels on the screen was given. The position of the response labels on the screen was counterbalanced across participants. Accuracy to the Response Verification Probe was used to determine which trials were to be analyzed. Imaging acquired for incorrect trials were not analyzed.

To assess neural responses to the three critical task phases, each phase was separated from one another by delays with randomly varied durations between two and eight seconds, according to an exponential distribution (Dale, 1999). The purpose of these delays is to reduce the collinearity between phases, and allowed for better estimation of the brain activity corresponding to each phase.

fMRI data processing. f*MRI preprocessing.* The data were preprocessed using SPM8 (Wellcome Trust Centre for Neuroimaging, Cambridge, UK). Functional volumes were corrected for slice timing acquisition, realigned to the first image within each run, normalized to the Montreal Neurological Institute (MNI) template, resampled to 2 mm^3 voxels, and smoothed using an 8 mm Gaussian kernel.

ROI Analyses. To best integrate our results with previous literature (Seo, Stocco, & Prat, 2018) which was based on a meta analysis of bilingual language control (Luk et al., 2012), nine spherical regions of interest (ROIs) were used for ROI analyses. As in our previous study, all of the ROIs had 8 mm radii, with the exception of three: the Pre-SMA radius was adjusted to 10 mm to cover both hemispheres, and the left and right BG (caudate) ROI spheres were reduced to 6 mm to prevent them from extending into functionally distinct neighboring regions. The size, MNI coordinates of the centroids, and corresponding Brodmann's areas (where applicable) of the nine ROIs used herein are listed in Table 3.

Table 3

Description of Interested Regions

Region	Centroid MNI Coordinates			BA	Radius (mm)
Left DLPFC	-44	13	29	46	8
Left Inferior Frontal	-48	15	11	44	8
Left Lateral Orbitofrontal	-31	18	-2	47	8
Left Middle Temporal	-48	-42	-6	37	8
Pre-SMA	1	1	57	6	10
Right Precentral	40	-9	32	6	8
Right Caudate	14	5	16		6
Left Caudate	-14	5	16		6
Anterior Cingulate Cortex	0	32	24		

Summary statistics for the ROI analyses were generated by averaging across the parameter values (i.e., beta weights) of all voxels within the ROI. Summary statistics were calculated independently for each combination of ROI, subject, cue type (informative cued, and non-informative cued), switching condition (switched versus repeated language) and over each of the three critical task phases (Prepare Target Language, Select Rule, Execute). The data were then analyzed separately for each ROI using 2 (cue type) x 2 (switch condition) x 3 (task phase) repeated measure analysis of variance (all effects were within-subject). All main effects and interaction were tested at a significance level of $p < 0.05$.

Individual differences analyses. To explore the neurocognitive effects associated with proactive and reactive control, we conducted a series of correlational analyses with the following aims: 1) To identify the proactive control networks, the proactive cuing effects (activation to informative cues > activation to non-informative cues) were computed across the two caudate ROIs and correlated with the proactive cuing effects in each of the other four lateral prefrontal ROIs. The logic behind this analysis is that individuals that use proactive control strategies should, according to Braver (2012), show increases in lateral prefrontal cortex with accompanied increases in dopaminergic circuits. In contrast, individuals who do not recruit proactive control mechanisms should show little or no differences between informative and non-informative cues; 2) To identify the reactive control networks, controlled execution effects (activation during execution of non-informative cued trials > activation during execution of informative cued trials) were computed in the ACC and the temporal lobe, and correlated with each of the other seven ROIs. The logic behind this analysis resembles the former, namely that according to Braver (2012), reactive control should result in a transient rise of activation during the execution phase, and this activation should be accompanied by either associative memory (temporal lobe) or conflict detection (anterior cingulate) mechanisms. Hence, reactive controllers should have smaller differences during execution of informative cued and non-informative cued trials in these areas than should proactive controllers. 3) To investigate the relation between proactive and reactive control, regions identified as part of the proactive control network through analysis one will be correlated with regions identified as part of the reactive control network in analysis two. Cuing effects in these regions should be anticorrelated. 4) To investigate the cognitive correlates of patterns of proactive and reactive control, cuing effects in the proactive and reactive control networks (identified through the first two analyses) will be correlated with cuing effects in response times.

Behavioral data analysis. An angular transformation was performed in accuracy data since the distribution of accuracy is not a normal. Incorrect response in Probe phases were excluded in the further analyses. Out of three phases (i.e., Prepare Target Language, Select Rule, and Execute), response times of Execute phases following non-informative cues versus informative cues were compared to test the impact of cues. Response times that were higher or lower than three standard deviation from the individual participants' mean were treated as outliers and excluded in response time analysis. As a result, 0.85% of response times in Execute phase were excluded in the response time comparison analysis. The time-out responses were replaced with the maximum time, 8000 milliseconds for the analyses. This constituted 3.43% of the data. A two by two by three repeated measure ANOVA was conducted on response times in switching, cue, and task phases. More specifically, factors were whether a target language in a trial was switched or repeated from the previous trial, and whether a target language was informed in Prepare Target Language phase or not.

4.3. Results

Behavioral results. Group means for accuracy across participants were 97.06% with a standard deviation of 1.61%. Because participants were highly accurate, behavioral analyses were run only on response times (to correct trials), after outliers defined as three standard deviations above and below the means were removed. The mean response times for each condition are listed in Table 4. A 2 (cue present or absent) x 2 (switch versus repeat) x 3 (task phase) repeated measures analysis of variance (ANOVA) revealed main effects of cuing [$F(1, 16) = 8.318$, $p = 0.011$] and task phase [$F(2, 32) = 34.477$, $p < 0.001$]. Follow-up analyses revealed that, consistent with our predictions, response times were longer in general for non-informative cued trials [Mean Difference (MD) = 150.505 ms $p = 0.011$] and in the execution phase [MD Execute and Prepare Target Language = 1546.774, $p < 0.001$; MD Execute and Select Rule = 1199.527, $p < 0.001$]. These results were modified by a significant cuing x phase interaction [$F(2, 32) = 9.862$ $p < 0.001$). Follow-up analyses showed that, consistent with the broader proactive control literature and our predictions, informative cued trials resulted in significantly faster execution phase response times [$t(16) = -5.279$ $p < 0.001$], whereas response times during preparation and rule selection were not significantly different for informative cued and non-informative cued blocks [Prepare Target Language: $t(16) = -0.631$, $p = 0.537$; Select Rule: $t(16) = -0.168$, $p = 0.869$]. No main effects or interactions with switching were found [$p = 0.974$].

Table 4.

Average Reaction Times (ms) in Task Phase by Informative and Non Informative Trial

	Informative	Non Informative	Switch	Repeat
Prepare Target Language	1165.94 (102.40)	1204.69 (129.90)	1151.19 (123.13)	1113.21 (104.50)
Select Rule	1447.30 (160.24)	1459.78(153.06)	1466.30 (174.07)	1486.88 (150.27)
Execute	2470.37 (278.79)	2891.68 (327.47)	2667.49 (298.94)	2690.03 (307.84)
Probe	724.73 (29.26)	716.87 (28.47)	712.50 (28.75)	729.45 (29.60)

Note. Standard errors of means are indicated in the parentheses. Item-priming-in-recognition analysis of probes.

Region of Interest (ROI) analyses. Parallel 2 (cue present or absent) x 2 (switch versus repeat) x 3 (task phase) ANOVAs were also conducted on each bilingual language control ROI. Consistent with our previous research, a main effect of task phase was observed in the left lateral frontal ROIs including DLPFC, lateral orbitofrontal cortex (BA 47), and IFG (BA 44), right precentral gyrus as well as in the medial Pre-SMA (See Figure 2). Follow-up analyses found that each of these areas had greater activation during execution than during encoding, consistent with the Execution Network described in our previous work (Seo et al., 2018).

Of particular interest to the current work, however, was a significant interaction between cuing and task phase, observed in both in Pre-SMA and left DLPFC. Follow-up comparisons demonstrate that these regions were more active during informative cued than non-informative cued trials over the preparation phase, and were correspondingly less active during the rule (Pre-SMA only) and execution (both) phases (See Figure 2). The remaining 4 rois (ACC, bilateral caudate, left middle temporal gyrus) were not modulated by our conditions of interest. Three of the four regions (bilateral caudate and left middle temporal gyrus) were designated as "consistent" language tracking networks in our previous research (Seo et al., 2018). *F*-statistics and follow-up paired *t*-statistics are reported in Table 5.

Figure 2.

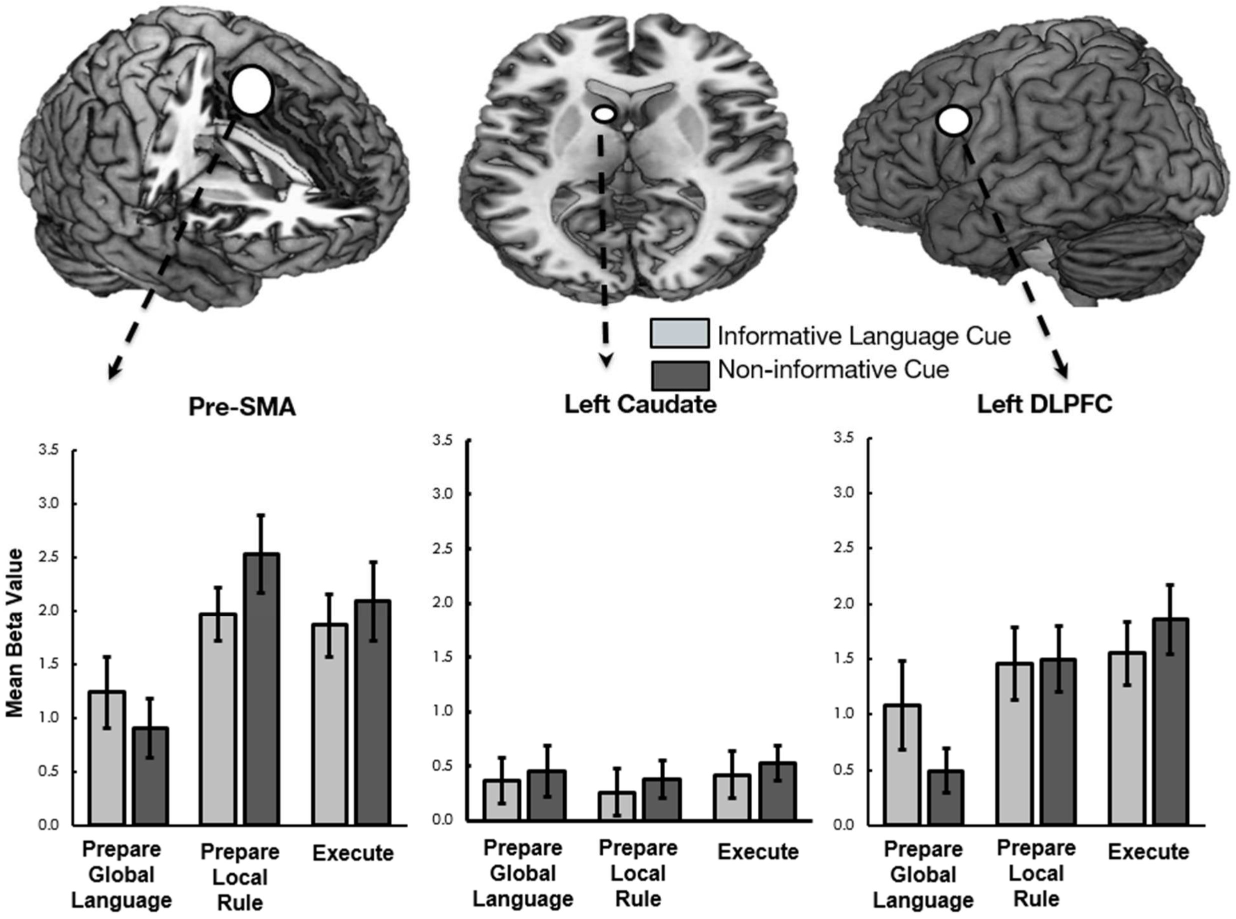


Figure 2. Mean beta weights extracted across the three task phases from three regions (pre-SMA, left caudate, left DLPFC).

Table 5

Statistics from 2x2x3 Repeated Measures ANOVA and Follow-up Tests for Cueing Effect and Task Phases on ROIs

(A) Significant Main Effect of Task Phase	*df*	*F*	*MSE*	*p*
Pre supplementary motor area	2	14.007	25.757	< 0.001
Left dorsolateral prefrontal cortex	2	16.112	15.446	< 0.001
Left inferior frontal gyrus	2	7.526	4.915	0.002
Left lateral orbitofrontal cortex	2	5.890	2.870	0.007
Right precentral	2	5.696	3.991	0.008
(B) Follow-up Effect of Phase	*Phase*	*MD*	*SEM*	*p*
Preparation				
Right Precentral gyrus				
	Prepare TL > Execution	0.416	0.171	0.027
	Select RL > Execution	0.423	0.104	0.001
Execution				
Pre supplementary motor area				
	Select RL > Prepare TL	1.176	0.181	< 0.001
	Execution > Prepare TL	0.903	0.269	0.004
Left dorsolateral prefrontal cortex				
	Select RL > Prepare TL	0.690	0.168	0.001
	Execution > Prepare TL	0.914	0.188	< 0.001
Left Inferior frontal gyrus				
	Execution > Prepare TL	0.537	0.154	0.003
	Execution > Select RL	0.287	0.113	0.021
Left lateral orbitofrontal cortex				
	Execution > Prepare TL	0.389	0.127	0.008
	Execution > Select RL	0.309	0.101	0.008
(C) Interaction	*df*	*F*	*MSE*	*p*
Pre-SMA	2	3.903	3.476	0.030
DLPFC	2	8.471	3.612	0.001

Note. The levels of each factor are as following:

Switching (2): Switching, Repeating

Phase (3): Prepare Target Language (TL), Select Rule (RL), Execution.

Individual differences analyses. ***Proactive control networks.*** Consistent with the neural mechanisms described by Braver (2012), the proactive cuing effect (informative > non-informative cues) in the left caudate nucleus was reliably positively correlated with the proactive cuing effects in three out of four of the lateral prefrontal regions of interest (ROI) including left DLPFC[$r(17) = 0.561$, $p = 0.019$], IFG[$r(17) = 0.563$, $p = 0.019$] and right precentral gyrus [$r(17) = 0.605$, $p = 0.010$] ROIs, as well as with the right caudate nucleus [$r(17) = 0.682$, $p = 0.003$]. The right caudate nucleus was only significantly correlated with cuing in the left DLPFC [$r(17) = 0.559$, $p = 0.020$]. To illustrate, the relation between cueing effects in the left IFG and left caudate nucleus are depicted in Figure 3.

Figure 3.

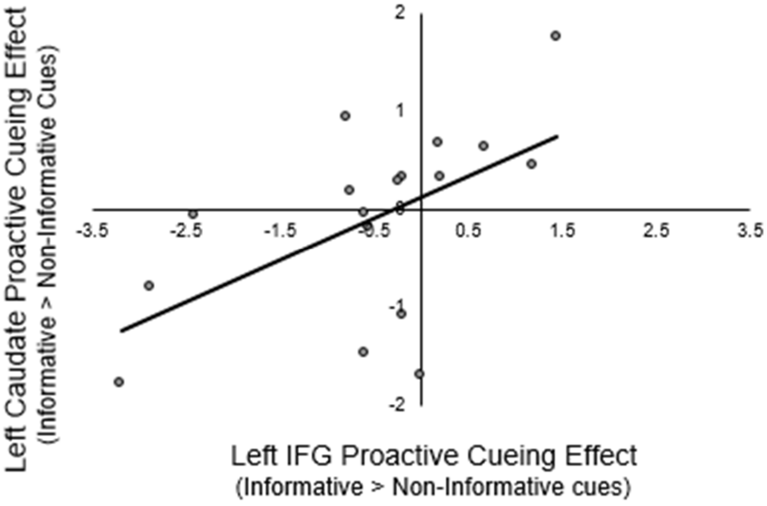
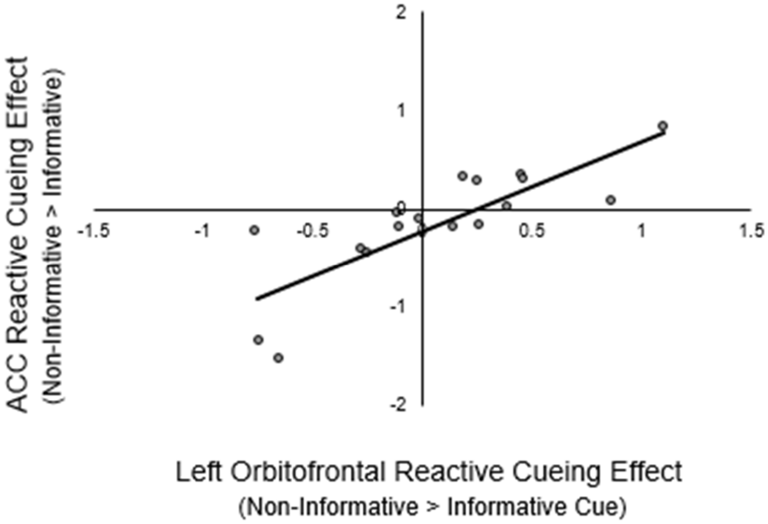


Figure 3. Scatterplot between left IFG proactive cueing effect and left caudate proactive cueing effect. Proactive cueing effect is the beta weight difference between informative cued > non-informative cued in Prepare Target Language phases, *r*(17) = 0.563, *p* = 0.019.

***Reactive control networks*.** The reactive cuing effect (execution of trials not preceded by informative cues > execution of trials preceded by informative cues) in the ACC was strongly positively correlated with reactive cuing effects in the left orbitofrontal ROI [$r(17) = 0.814$ $p < .001$] as well as with the Pre Supplementary Motor Area (Pre-SMA) [$r(17) = 0.518$, $p = 0.033$]. Patterns of connectivity to the other candidate reactive control mechanism, the left temporal ROI, were quite different. Specifically, the reactive cuing effect in the left temporal ROI positively correlated with the reactive cuing effects in the lateral prefrontal regions including the left DLPFC [$r(17) = 0.614$, $p = 0.009$], the left IFG [$r(17) = 0.523$, $p = 0.031$] and the right precentral gyrus [$r(17) = 0.588$, $p = 0.013$] ROIs. To illustrate, the relation between reactive cueing effects in the ACC and left orbitofrontal ROI and between the left medial temporal and DLPFC regions are depicted in Figure 4a, 4b.

Figure 4a.



2
1
0
-1
-2
-1.5
-1
-0.5
0.5
1
1.5
ACC Reactive Cueing Effect
(Non-Informative > Informative)
Left Orbitofrontal Reactive Cueing Effect
(Non-Informative > Informative Cue)

Figure 4b.

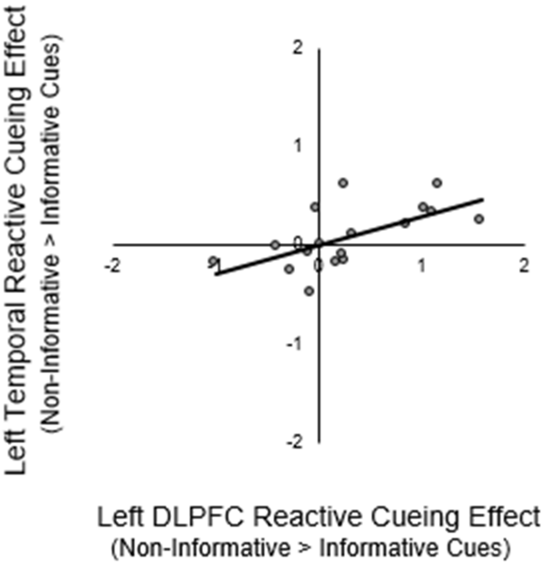


Figure 4a. Scatterplot between left Orbitofrontal reactive cueing effect and ACC reactive cueing effect. Reactive cueing effect is the beta weight difference between non-informative cued > informative cued in Execute phases, *r*(17) = 0.814, *p* < 0.001. 4b. Scatter plot between left DLPFC reactive cuing effect and left temporal reactive cueing effect, *r*(17) = 0.614, *p* = 0.009.

Relating proactive control to reactive conflict **networks**. The relation between proactive (activation during informative > non-informative cues) and reactive (activation during execution of non-informative > informative trials) cueing effects was generally negative. Specifically, the cueing effects of three lateral prefrontal regions, DLPFC, IFG, and right precentral gyrus correlated with reactive execution effects in distributed ROIs. The correlations with left IFG cueing effects were most strongest and most distributed, reaching significance with the reactive execution effects of five out of nine ROIs including the left IFG [$r(17) = -0.697$, $p = 0.002$], orbitofrontal [$r(17) = -0.631$, $p = 0.007$], and DLPFC [$r(17) = -0.764$, $p < 0.001$], right precentral gyrus [$r(17) = -0.507$, $p = 0.038$], and Pre-SMA [$r(17) = -0.754$, $p < 0.001$]. Cuing effects in left DLPFC also negatively correlated with the reaction execution effects in the left DLPFC [$r(17) = -0.549$, $p = 0.023$], the ACC [$r(17) = -0.535$, $p = 0.027$] and with the right caudate nucleus [$r(17) = -0.584$, $p = 0.014$]. Right precentral gyrus [$r(17) = -0.507$, $p = 0.038$], and cueing effects in the right precentral gyrus ROI were negatively correlated with reactive execution effects in the left DLPFC [$r(17) = -0.628$, $p = 0.007$] and right precentral gyrus [$r(17) = -0.528$, $p = 0.029$] ROIs.

Relating proactive and reactive control networks to cognitive demands. Neither proactive nor reactive control effects were reliably predictive of task response times, although the proactive cuing effect in the left caudate approached significance with the cueing effect observed during the probe verification phase [$r(17) = .43$, $p = .087$].

4.4. Discussion

The results reported herein provide a unique opportunity to leverage the predictions of the dual mechanisms of cognitive control framework to better understand proactive and reactive language control. Consistent with previous research (Grainger, Declerck, Marzouki, 2017; Martin, Molnar, Carreiras, 2016; Woumans et al., 2015), we found that the presence of preparatory language cues facilitated subsequent execution of a morphosyntactic rule. This is the first study, however, to link this effect to patterns of neural activation. At the group level, a cue by task phase interaction was reflected by patterns of activation in the DLPFC and Pre-SMA ROIs (Figure 2); however, considerable individual differences in the extent to which bilinguals employed “proactive” versus “reactive” strategies were also observed. Below we describe both the group and individual differences results in light of the larger literature on the neurocognitive basis of bilingual language control.

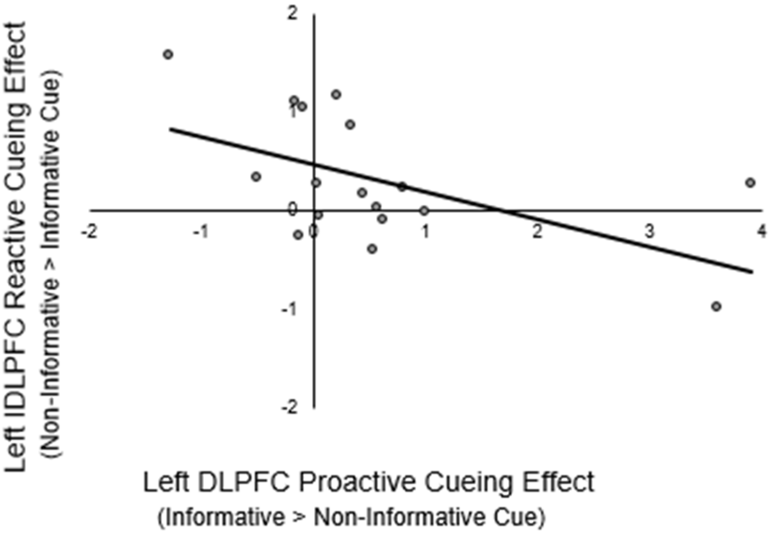
Understanding the role of the lateral prefrontal cortical regions in bilingual language control. The current study compared patterns of activation across four lateral prefrontal ROIs, left IFG, DLPFC, orbital frontal, and right precentral gyrus, which have been widely implicated in bilingual language control (e.g., Seo et al., 2018; Luk et al., 2012). To the best of our knowledge, the dual mechanism framework does not make specific predictions about how these regions might differ from one another, but instead makes predictions about when they will be differentially activated in proactive and reactive control, and with which regions they may co-activate. Three of these four regions, the IFG, DLPFC, and right precentral gyrus, show patterns consistent with the dual mechanism framework in that the extent to which these regions were sensitive to informative target language cues was correlated with activation in the dopaminergic basal ganglia nuclei. The orbitofrontal cortex, on the other hand, showed a pattern of activation more in line with reactive control or conflict monitoring, correlating strongly with reactive execution sensitivity in the ACC (Figure 4a).

The adaptive control hypothesis, on the other hand, suggests that the right precentral gyrus will be involved in salient cue detection or inhibitory control processes, whereas the DLPFC and IFG will be involved in the control of both global and local interference, possibly through response selection (Abutalebi et al., 2016). Although the general patterns of these three regions with respect to individual differences in proactive and reactive control did not differ, the overall direction of their responses at the group level did differ in an interesting way. First, consistent with our previous work, the two left prefrontal ROIs showed a general increase in activation from global to local task instruction phases through execution; whereas the right precentral gyrus did not (Seo et al., 2018: See Figure 2). In the current experiment, the right precentral gyrus at the group level was equally active for informative cued and non-informative cued trials during all preparatory phases, but was not engaged in task execution. In our previous research, right precentral gyrus remained consistently activated across task phases and execution. Across experiments, the consistent engagement of right precentral gyrus for global language selection and local rule selection phases suggests that the right precentral gyrus may be engaged either in the process of detecting salient cues, which are presented at each phase of the trial, or in some kind of general inhibitory process. It is unclear why at the group level the right precentral gyrus did not show differential responses to informative versus non-informative target language cues, but individual differences analyses suggest that this was the case for some individuals and not others. We see this as an interesting avenue for future research.

The current experiment replicates and extends our previous research on the role of the left lateral frontal regions in bilingual language control (Seo et al., 2018). Both the current and previous research show that left lateral frontal regions show increased activation from global language preparation phases, to local rule selection phases, with the highest activation during task execution; however, the current experiment shows that these regions are differentially sensitive to global language cues. The DLPFC showed responses that are consistent with a working memory or goal maintenance view of bilingual language control. As evidenced by the significant cue by phase interaction (Figure 2), DLPFC activation was reliably greater to informative than to non-informative cues, and was subsequently less active in informative cued versus non-informative cued trial execution. In contrast, the IFG showed a pattern of responding that is more consistent with conflict management or response selection processes. Although the main effect of cueing was not significant ($p = 0.087$), IFG activation was generally greater for trials that began with non-informative cues, both during cuing and execution. As there was no specific instruction to hold in mind during non-informative cues, this pattern of responses suggests that the IFG responds in an anticipatory way to upcoming response conflict. The left orbitofrontal cortex was generally not sensitive to global language cueing at the group level.

Further evidence for a dissociation between the roles of left DLPFC, and IFG can be seen in the individual differences results. For example, Figure 5a, and 5b show the relation between proactive and reactive cueing effects in the DLPFC and IFG. Consistent with a dual mechanism framework, the cueing effects in DLPFC were generally positive (Figure 5a, right of zero on x-axis) and the extent to which an individual increased activation in DLPFC for informative cued trials carried over to execution, resulting in a negative reactive execution effect (non-informative cued > informative cued: below zero on y axis). In contrast, people who showed little difference between DLPFC activation to informative versus non-informative cues, or showed greater activation to the latter (Figure 5a, left of zero of x axis) showed large reactive control effects during execution (above zero on the Y axis). Consistent with an interference management view, individuals who had a stronger IFG response to non-informative cues (Figure 5b, left of zero on x axis) also showed a stronger IFG response for non-informative trial execution (Figure 5B above zero on Y axis). Further evidence for dissociable roles of the DLPFC and IFG can be seen by the stronger and more widespread correlations between the proactive interference responses of IFG and the reactive execution responses of many of the regions in the bilingual language control network. We see this as an interesting avenue for future exploration.

Figure 5a.


2
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Left lDLPFC Reactive Cueing Effect
(Non-Informative > Informative Cue)
Left DLPFC Proactive Cueing Effect
(Informative > Non-Informative Cue)

Figure 5b.

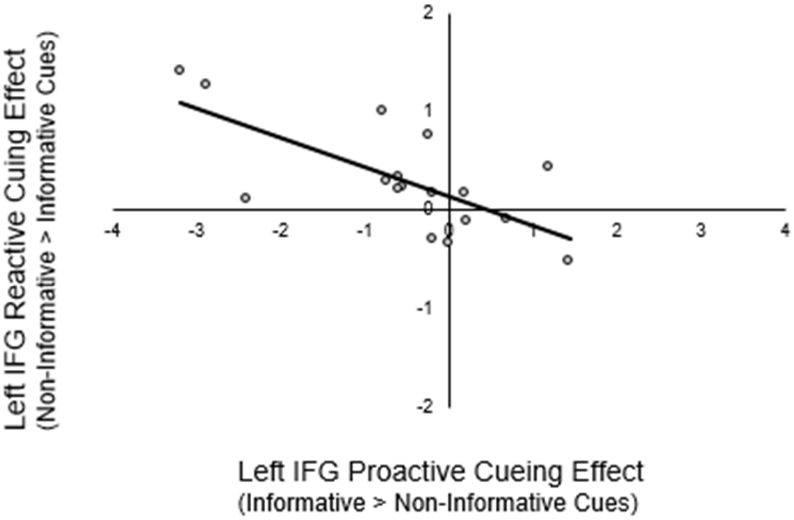

Figure 5a. Scatterplot between left DLPFC cueing effect and left DLPFC reactive cueing effect, $r(17) = -0.549$, $p = 0.023$. Proactive cueing effect is the beta weight difference between informative cued > non-informative cued in Prepare Target Language phases. Reactive cueing effect is the beta weight difference between non-informative cued > informative cued in Execute phases. *5b*. Scatter plot between left IFG proactive cuing effect and left IFG reactive cueing effect, $r(17) = -0.697$, $p = 0.002$.

Understanding the role of the basal ganglia nuclei in bilingual language control. A considerable amount of experimental (See review: Luk et al., 2012; Crinion et al., 2006) and theoretical (Abutalebi, 2008; Friederici, 2006) research has implicated the left caudate nucleus in bilingual language control. The current experiment extends this body of work in important ways. First, along with the meta-analysis of Luk et al. (2012), and our previous research (Seo et al., 2018), we found that both left and right caudates are involved in bilingual language control. Specifically, across both experiments, we showed that the left and right caudates remained consistently active across task preparation and execution phases. Although very little research to date has investigated laterality of language processes in the striatum, our results are inconsistent with the explanation of fronto-striatal laterality proposed by Crosson (2003), who suggested that right basal ganglia activation in absence of right precentral gyrus activation reflected an inhibition of right frontal regions during a language production task. The correlation between cueing effects in the right caudate and the right precentral gyrus ROI did not reach significance, but it did approach significance and was in a *positive* direction [$r(17) = .44$, $p = .077$]. Also, the cuing effects in the left and right caudates were strongly positively correlated with one another[$r(17) = 0.682$, $p = 0.003$].

The results of the current research contribute two new pieces of evidence about the role of the bilateral caudates in bilingual language control: 1) that they are not differentially activated as a function of language switching versus repeating across trials, and 2) that individual differences in sensitivity to global language cues, manifest by differences in activation between informative versus non-informative language cues in the striatum, correspond to individual differences in activation in prefrontal control regions, and to a marginal degree to differences in performance on informative cued versus non-informative cued trials ($p < 0.10$). These results can be viewed in light of the existing theories of the role of the basal ganglia in “keeping track” of target language in use.

The results reported herein are consistent with the role of fronto-striatal signal biasing systems described in the conditional signal routing model of bilingual language control (Becker et al., 2016; Buchweitz & Prat, 2013; Stocco et al., 2014; Stocco & Prat, 2014; Yamasaki, Stocco, Liu & Prat, under review). Specifically, the conditional signal routing models suggested that bilingual language control is achieved by the striatum prioritizing certain signals converging on the prefrontal cortex, according to the target language in use. The current study supports this explanation by showing that striatal responses to information about target language are correlated with the responses of three target areas in the prefrontal cortex. It also extends this description by showing that the extent to which such signal prioritization is done proactively versus reactively varies across participants.

Understanding the role of the ACC/Pre-SMA regions in bilingual language control. The ACC and pre-SMA have been jointly associated with conflict monitoring in both the general cognitive control literature (Duncan, 2010; Garavan et al., 2002; Milham et al., 2001; Hester et al., 2004), and in the bilingual language control literature (Abutalebi, Della Rosa, Ding, Weekes, Costa, Green, 2013). Both our previous and current research show differential patterns of responding in the ACC and pre-SMA. Specifically, Seo et al. (2018) found that the ACC was most active during global language preparation, whereas the pre-SMA showed increased activation across the phases, with greatest activation during execution. Following that study, we proposed that the ACC activation during global language preparation might have been particularly driven by trials in which the target language switched from one task to another; however, the current experiment found that this was not the case. At the group level, ACC activation in the current experiment did not vary as a function of language switching, language cueing, or task phase. In contrast, the group level patterns of activation in pre-SMA in both the previous and current research showed that activation in pre-SMA increased across global language preparation, local rule preparation, and execution phases. A significant cue by phase interaction was observed in the current study, suggesting that proactive global language cues resulted in decreased pre-SMA activation during local rule selection and rule execution phases.

Importantly, the presence of both informative and non-informative global language cues in the current study allowed us to investigate individual differences in the extent to which the ACC was sensitive to information about global language conflict either proactively or reactively. Here, the results showed that sensitivity to conflict during task execution for non-informative cued versus informative cued trials was highly correlated between the ACC, Pre-SMA, and orbital frontal regions. One review paper suggests a possible explanation for the dissociation of the ACC and Pre-SMA in conflict monitoring and switching. Specifically, Hikosaka and Isoda (2010) propose that the ACC is more sensitive to a negative feedback loop, whereas the Pre-SMA is more active in switching behavioral responses following a cue. Although no explicit feedback was provided in the current trials, the role of the Pre-SMA in motor preparation or suppression following informative cued responses is consistent with the patterns of activation reported herein, especially if one considers competition both across languages (global competition) and across rules (local competition) which is consistent with a broader role of the Pre-SMA in rule-based behaviors (Hester et al., 2004) and with our previous research showing that bilinguals experience stronger conflict in LITL tasks between rules within a language than across languages (Seo and Prat, under revision).

Role of the middle temporal lobe and memory retrieval. Although the left middle temporal lobe has been implicated in meta-analyses of bilingual language control (Luk at al., 2012), it is not included in the bilingual language control network described in the Adaptive Control Hypothesis. In contrast, the dual mechanisms framework suggests that associative memory processes in medial temporal regions may trigger reactive retrieval of relevant task goals. Taken together, the results of the current experiment as well as our previous research, suggest that the middle temporal ROI was consistently activated across task phases, and in conditions with or without informative global language cues. Importantly, the consistent activation of middle temporal lobes in the current experiment suggests that its involvement in our previous study was not tied to the memory demands associated with retrieving the mapping between abstract task rules and linguistic cues (e.g., # = Spanish trial). Additionally, individual differences results suggested that reactive control in the left temporal lobe (increased activation during execution of trials preceded by non-informative versus informative cues) was positively correlated with similar reactive cueing effects in the three lateral prefrontal regions that were associated with proactive control. This is largely consistent with the reactive control mechanism proposed in the dual mechanism framework (Braver, 2012), suggesting that when an individual fails to maintain a task instruction or goal prior to task execution, the left temporal lobe co-activates with frontal regions in a manner that resembles memory retrieval.

Importance of individual differences research. Although the current results were conducted on a relatively small sample, the exploration of individual differences reported herein provide important modifications of our understanding of several regions of interest. Specifically, the Pre-SMA, DLPFC, IFG, and orbitofrontal areas all showed increasing patterns of activation across task phases at the group level in current and previous research (Seo et al., 2018). Seo et al.

(2018) discussed this increase in activation as possibly arising from the accumulation of information in working memory. The addition of non-informative cued trials in the current experiment allowed us to explore individual sensitivity to the information presented in each of these phases. The results suggest, consistent with the dual mechanism framework, that two patterns of activation emerge across individuals. The first, proactive control pattern, shows early and sustained activation in the face of proactive global language cues, or the lack thereof in the case of IFG conflict monitoring. The second, reactive control pattern, shows late and transient activation during reactive task execution. When these patterns are summed across individuals, one gets the impression that activation is gradually increasing across tasks. In fact, this pattern of activation is not commonly seen at the individual level. To illustrate, Figure 6 depicts patterns of DLPFC activation across informative cued task trials in two individuals. The first individual (in dark grey) shows a proactive pattern of activation and the second individual (in light grey) shows a reactive pattern of activation.

Figure 6.

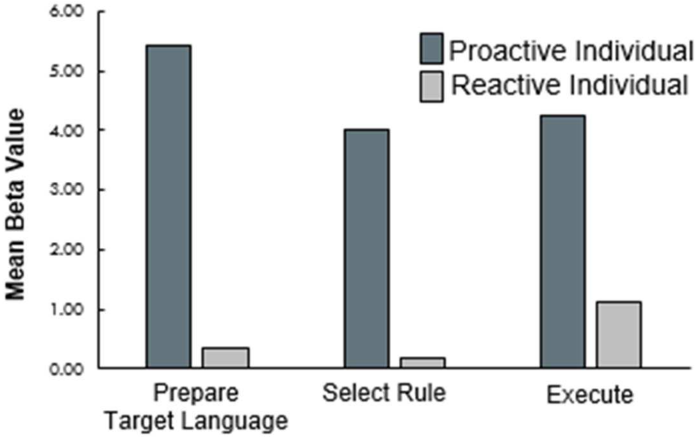

Figure 6. Two individual’s beta weights extracted across the three task phases in cued trials.

4.5. Conclusion

With a noble informative and non-informative cued design, current study was able to dissociate the neural basis of proactive and reactive control mechanisms in bilingual language control. Proactive control is achieved by a network between prefrontal cortex and the basal ganglia and reactive control is by the ACC and the left orbitofrontal cortex. The negative correlation between proactive and reactive cueing effect in the DLPFC and IFG also adds the evidence of the dual mechanisms. Results from the individual difference analyses support for the preferences across individuals in adapting proactive control over reactive control and vice versa. It will be an interesting study to follow up with investigation of the predictors of these choice with bilingual individuals with various language profiles.

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Chapter 5. Discussion

My doctoral research culminated in three publications reporting the results of four experiments (two neuroimaging experiments and two behavioral experiments) investigating bilingual language control in Spanish-English bilinguals using RITL paradigms. Although the complexity of these experiments decreased from the first publication, which used abstract symbols to represent 16 different morpho-syntactic rules, to the third publication, which used semantically relevant stimuli to represent four morpho-syntactic rules, each of the experiments yielded results that extended, yet were consistent with the broader literature on bilingual language control, cognitive control, and cognitive flexibility. Thus, data collected across my experiments highlights the utility of using RITL paradigms manipulating linguistic stimuli to understand bilingual language control processes. Below I summarize how this body of research has both replicated and extended the broader literature on the neurocognitive bases of bilingual language control, organized around my original research questions.

5.1. Morpho-Syntactic Rule Execution Recruits Regions Previously Implicated in Lexico-semantic Tasks

To the best of my knowledge, my doctoral research was the first to examine the extent to which the network of regions previously identified using only lexical tasks (primarily naming) was implicated in morpho-syntactic execution. Across two neuroimaging experiments using RITL tasks (Seo, Stocco & Prat, 2018; Seo & Prat, *under review*), we showed that the network of regions identified by Luk and colleagues (2012) as well as the ACC, which is central to the ACH, were reliably activated in morpho-syntactic rule execution. Our results were also largely overlapping with those obtained from more naturalistic (e.g., picture naming) experiments, and did not vary widely when abstract symbols (Seo et al., 2018) and more semantically relevant symbols (Seo & Prat, under review) were used.

Across these two experiments, we observed three patterns of activation, which will be discussed subsequently in light of my research questions. First, we identified a series of regions that showed a "ramping up" pattern of activation from preparation to execution which were identified as the "Execution" network. Across both studies, the three left lateral prefrontal and midline pre-SMA regions showed this pattern of results. A second "stable" patterns of activation across task phases, which we called the "language tracking" network was found in bilateral caudate nuclei and left temporal networks across both experiments. Finally, in the first experiment (Seo et al., 2018) the ACC alone showed a "preparatory" pattern of activation, with highest activation during the global language preparation phase. In the follow-up experiment (Seo & Prat, under review), however, when presence or absence of global language cues was manipulated, the ACC showed a more stable pattern of activation across task phases. These findings are discussed in more detail below. Additionally, in the first experiment (Seo et al., 2018) the right prefrontal regions showed a ramping up pattern of activation, consistent with the Execution network. In contrast, in the follow-up experiment (Seo & Prat, under review), right precentral showed a "preparation" pattern of activation, with significantly greater activation during preparation than during execution. Taken together, these results provide the first evidence for different mechanisms deployed during preparation (proactive control) and execution (reactive control) as well as during global (target language) and local (morpho-syntactic rule) control processes.

5.2. Global and Local Control Mechanisms Recruit Separable but Overlapping Neural Mechanisms

One of the most salient, novel pieces of information obtained from my research is how widespread the patterns of activation are for global language control. In my original experiment, where target language information was reliably presented at the beginning of a trial, the ACC was uniquely activated during global language control processes. whereas no single region was selectively responsive, or most responsive, to local control. In fact, all regions that increased from global to local control phases, also increased during execution, suggesting a possible working memory function. Additionally, general linear model analyses showed greater activation during global than local processes (Seo et al., 2018, Figure 4).

Importantly, the cued conditions of the follow-up experiment (Seo & Prat, under review.) replicated these patterns. Although not reported in the publication, results from the general linear model showed highly distributed, and overlapping patterns of activation during global target language preparation phase, as opposed to a more focal pattern of activation over the same regions during local morpho-syntactic rule selection phases. Taken together, the results from Seo et al., 2018 and Seo and Prat, under review suggest that a bilaterally distributed, primarily frontal network of regions is involved in both global and local language selection processes. In the discussion of Seo and Prat, under review, I propose some possible further distinctions between the roles of the left and right prefrontal ROIs in language selection and inhibition across these phases.

5.3. Global Language Control Mechanisms Are More Efficient than are Local Control Mechanisms

In Seo and Prat, under revision, I reported the results from two behavioral experiments that demonstrated the primacy of global language control mechanisms for bilingual language control. Specifically, my results showed that irrespective of the presentation order of global language information, bilingual individuals were more effective in inhibiting competing rules across languages than within languages. The primacy of this global language control was shown in the reaction time differences when rejecting probes reflecting rules in the non-target language as compared to rejecting probes reflecting incorrect rules in the language being employed during the task. These findings are consistent with recent electrophysiological results, which showed that bilingual individuals can use information about the target language of a word to inhibit subsequent semantic processing, but cannot use semantic information to inhibit processing of the target language (Hoversten, Brothers, Swaab, & Traxler, 2015)

5.4. Variability in Proactive and Reactive Bilingual Global Language Control Mechanisms

Although there were some implications of this in Seo et al., 2018, the final neuroimaging investigation systematically investigated proactive and reactive control mechanisms during bilingual morpho-syntactic rule execution. At the group level, we showed that the DLPFC and Pre-SMA regions showed cue x task-phase interactions, suggesting that an increased sensitivity to informative language cues resulted in less activation during either local rule selection or task execution phases. A similar interaction was observed in behavior, showing that all bilinguals were faster to execute morpho-syntactic rules when they were preceded by a cue about which language would be used. From a cognitive perspective, our results add to a mounting literature showing that proactive cues about target language facilitate bilingual performance (Martin, Molnar & Carreiras, 2016; Woumans et al., 2015).

These results add to this literature by grounding it in the neurocognitive bases of proactive and reactive cognitive control described by Braver (2012). Importantly, we adopted both the proposed neural mechanisms described by Braver (2012) and the centrality of individual differences in preference of taking proactive strategies over reactive strategies. In doing so, I was able to show that individuals vary in the extent to which they use information provided proactively to guide their language control processes. When looking at patterns of performance within individuals, I was able to show that, consistent with the dual mechanisms framework, the lateral prefrontal ROIs work in concert with the basal ganglia nuclei, and can do so either proactively or reactively. Similarly, I showed that the ACC, Pre-SMA, and left orbital frontal network work in concert to detect conflict reactively. These results provide critical new information, showing that the patterns of activation obtained from group-level data in both neuroimaging investigations do not perfectly describe the patterns of activation of individuals in the group. I see this as an important area of investigation for future experiments, which may also take into account differences in the patterns of language use employed in bilinguals' daily lives. Such individual differences in language use should produce differences in the deployment of cognitive control mechanisms, according to the ACH.

5.5. What is in Control of Bilingual Language?

In the subsequent section, I integrate the findings of my doctoral research with the existing literature on two general cognitive control networks that have been consistently implicated in bilingual language control research: the ACC and basal ganglia. Both regions are central to the ACH which proposes that the ACC monitors conflict and the basal ganglia execute language switching behaviors. Importantly, in the one experiment in which we systematically investigated language switching (versus repeating), neither region was differentially active to switch conditions (Seo & Prat, under review).

5.5.1. The role of the anterior cingulate cortex. The ACC, along with the Pre-SMA has been associated with bilingual language control, through a general role in conflict monitoring (Badgaiyan & Posner, 1998; Barber & Carter, 2004; Botvinick et al., 1999; Carter et al., 1998) or error detection (Hester, Foxe, Molholm, Shpaner, & Garavan, 2005), which are believed to be brought online when multiple stimuli compete for selection (Bush, Luu, & Posner, 2000). In line with the general cognitive control view, the ACC has been associated with language conflict experience in bilingual language processing (Abutalebi et al., 2011; Rodriguez-Fornells et al., 2005; Van Heuven, Schriefers, Dijkstra, & Hagoort, 2008). Guo et al. (2013) observed the ACC activation during switching L2 to L1 for bilinguals. In support of this hypothesis, they found reliable structural differences in ACC associated with bilingual language experience (Abutalebi et al., 2011). Specifically, bilingual individuals showed increased grey matter density in the ACC compared to monolingual speakers (Abutalebi et al., 2011).

While my research suggested a role of the ACC in bilingual language control, the precise nature of its involvement varied across participants (Seo & Prat, under review) and across task conditions (Seo et al., 2018 versus Seo & Prat, under review). Importantly, in both experiments, and inconsistent with the ACH, the ACC and pre-SMA showed different patterns of activation during bilingual language control. This dichotomy highlights a difference between the interplay of these regions observed in dual control frameworks (Hikosaka & Isoda, 2010) and in bilingual language processing context (Abutalebi & Green, 2016). Specifically, Price and colleagues showed that Pre-SMA was specifically activated during speech initiation (Price, 2010). Because each of my experiments employed “sub-vocal” production tasks, it is unclear what to make specifically of the difference between ACC and Pre-SMA involvement in conflict monitoring. We see this as an important area for future research.

5.5.2. The role of basal ganglia. The bilateral caudate nuclei have been widely implicated in theories of bilingual language control from the ACH, which was the centerpiece of my dissertation (Abutalebi & Green 2016; Green & Abutalebi, 2013) to the Conditional Signal

Routing model of bilingual language control, originally proposed by my advisors (Becker et al., 2016; Buchweitz & Prat, 2013; Stocco, Yamasaki, Natalenko, & Prat, 2014). In both models, the caudate nuclei are generally proposed to be responsible for "tracking" global language information, and have thus been named a critical locus of bilingual language control.

Specifically, through dopaminergic pathways connecting to the prefrontal cortex, the caudate nuclei are reported to prioritize signaling of stimuli in the desired target language (Abutalebi et al., 2007; Crinion et al., 2006; Ford et al., 2013; Stocco et al., 2014) to the prefrontal cortex. Research on the role of the caudate nuclei in global language tracking include an influential paper using automatic priming in three different groups of bilinguals, showing that when they perform a lexical decision task and see semantically related words in different languages (e.g., cat-perro), a corresponding reduction in activation occurs throughout a distributed semantic network, with the exception of the left caudate nucleus (Crinion et al., 2006). This was taken as evidence that the head of the left caudate nucleus in particular "keeps track" of global language information (e.g., Friederici, 2006). This is also consistent with the conditional signal routing model (Stocco et al., 2014), which proposes that the basal ganglia more broadly "keeps track" of varying contexts which would dictate the subset of stimuli, features, or response patterns that would most likely be rewarding. In this view, "target language" can be seen as an important global context for tracking which local information (e.g., dog versus perro) would be more likely to be rewarding when trying to communicate. Further evidence for the role of the caudate nuclei in global language tracking can be seen from bilingual patient studies, which have shown that stimulation of the caudate, or damage to this region can result in pathological switching in bilingual individuals (Buchweitz & Prat, 2013; Fabbro, 2001; Stocco et al., 2014).

Results from the two neuroimaging experiments provide converging support that bilateral basal ganglia nuclei are critical for global language control. Specifically, unlike Crinion's lexical priming paper, during morpho-syntactic rule execution, bilateral caudate nuclei were stably active across all task phases. Interestingly, each phase in the RITL task requires different computations, but for all phases it is important to know what language a task will be executed in. The stable caudate activation across task phases implies that they are involved in maintaining information about target language. Additionally, individual differences research showed a strong correlation between left and right caudate nuclei and the dorsolateral prefrontal (DLPFC) cortex in their responses to global language cues. The strong correlation is consistent with conditional signal routing and the dual mechanisms framework, demonstrating the role of dopaminergic gating systems on goal maintenance and context monitoring.

One interesting and novel finding in my experiments was that although ROI analysis implicated the bilateral caudate nuclei equally and stably across task phases, distribution of activation analyses suggested that across task phases, and across participants, the striatum showed distributed, overlapping patterns of activation in left caudate and putamen; whereas the right caudate nucleus showed patterns of activation that were unique to each task phase (Seo et al., Figure 5). This is interesting when viewed in the fact of the specific pattern of activation in the left caudate nucleus previously indicated in lexico-semantic priming (Crinion et al., 2006) as opposed to the right caudate nucleus, which was implicated in the meta-analysis of language control studies (Luk et al., 2012). To the best of our knowledge only one paper to date has specified different roles of the caudate nuclei in language control (Crosson et al, 2003) based on their interactions with lateral prefrontal regions. We see this as an important avenue for future investigations.

Chapter 6. Summary

Taken together, the results from four publications based on three novel experiments converge to suggest the centrality of global language control as a mechanism for bilingual language control. This is particularly important given that monolingual individuals, who have primarily been the basis of our investigations of language processes in the brain, do not *need* global language control and hence, much less is known about the mechanisms by which it is accomplished. Global language control in bilingual was shown to be more effective than local language control in reducing conflict (Seo & Prat, under review) and to recruit a broader network of cognitive control regions than local language control (Seo et al., 2018; Seo & Prat, under review). Global language control can also be deployed proactively, to compute which word forms or rules will most likely be rewarding in advance, or on the fly, when conflict between competing languages is detected in the brain. Importantly, when global language cues are available, and when bilingual individuals take advantage of such cues, they are able to facilitate subsequent linguistic processes. While the precise mechanisms of global language control are still under investigation, the research reported herein suggests that the bilateral caudate nuclei and bilateral prefrontal cortices are jointly involved, consistent with the Conditional Signal Routing model of basal ganglia functioning.

Chapter 7. References

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