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The bilingual language network: Differential involvement of anterior cingulate, basal ganglia and prefrontal cortex in preparation, monitoring, and execution

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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 processes 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.

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 et al., 1999; Hatzidaki et al., 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 et al., 2011; Branzi et al., 2015; Hoversten et al., 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 et al. (2000) used a picture-naming paradigm in which the target language either switched between Spanish and English or

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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 et al., 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 et al., 2009) the DLPFC is involved in goal maintenance or storing a set of rules for behaving given specific conditions (Miller and Cohen, 2001; Wallis et al., 2001; Cole et al., 2010; Becker et al., 2016).

In parallel, evidence from neuropsychological (e.g., Abutalebi et al., 2000; Fabbro, 2001), neurosurgical (Robles et al., 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 et al., 2014; Stocco et al., 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 and 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 and Abutalebi, 2013; Abutalebi and Green, 2016) included an important role for the ACC, which is generally characterized as a region that detects or monitors conflict (e.g., Botvinick et al., 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 et al., 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 et al., 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 more subtle (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 2,000 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 and Carlson, 2000; Ruge et al., 2013; Zhang et al., 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 and 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 and 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