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THE ROLE OF PROFICIENCY ON THE USE OF COGNITIVE CONTROL DURING SECOND LANGUAGE PROCESSING

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ABSTRACT

This dissertation examines the use of cognitive control during second language (L2) processing by adult language learners. Although cognitive control has been acknowledged as an important component of language processing for many years, its conception in the language literature was largely as a top-down mechanism of inhibition. In two experiments I explore the role of a complementary type of cognitive control, bottom-up control, and how second language proficiency modulates its use.

Experiment 1, a functional MRI study, investigated the blood-oxygen-level-dependent (BOLD) signal correlates of bottom-up and top-down non-linguistic control, as well as semantic processing in the L1 and L2 by Spanish learners varying in proficiency. I found that high proficiency learners showed less activation in the caudate nucleus (CN), a crucial component of the top-down control network, and increased activation in the cerebellum and superior temporal gyrus, two areas associated with bottom-up control. I additionally observed that the multivariate activity patterns in regions associated with top-down control (including the CN and prefrontal cortex) were more similar in high proficiency learners, and that the connectivity between these regions was more efficient than in low proficiency learners.

Experiment 2 considered how training on top-down and bottom-up control could affect acquisition of new foreign language vocabulary, and found that top-down control training significantly speeded responses compared to bottom-up training and a sham condition. Together, these experiments suggest that low proficiency learners rely more on top-down control during L2 processing, while high proficiency learners may transition to a more bottom-up control process mediated by more posterior regions associated with cue detection and selective attention. These findings provide empirical support for the relevance of the conceptual distinction between top-down and bottom-up control to language learning. Furthermore, applying this distinction allows for the reconciliation of current theories of language learning, which differ in their predictions concerning the role of proficiency in how language learners use cognitive control.

TABLE OF CONTENTS

List of Tables

List of Figures

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Chapter 1: Introduction to L2 Acquisition and Cognitive Control

The acquisition of a second language is inherently advantageous in that it opens up an entire new population of speakers to interact with. In addition to this, however, research in recent years has begun to uncover that bilingualism may affect our neuroplasticity more generally. These differences range from reduced pro-active interference in children, to monitoring advantages in young adults, episodic recall advantages in middle age, and delayed dementia symptoms in old age (Bialystok, Craik & Freedman, 2007; Bialystok & Feng, 2008; Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009; Ljungberg, Hansson, Andrés, Josefsson & Nilsson, 2012). Much remains to be discovered about the effect of bilingualism on mind and brain, however. Whether bilingualism has a causal effect on cognitive control skills, for example, has yet to be established (although see promising work from Sullivan, Janus, Moreno, Astheimer & Bialystok, 2014). If second language (L2) acquisition does have a causal effect on cognitive control, the implications for preventative care and dementia therapy could be enormous (Antoniou et al., 2013).

In order to determine if bilingualism has a causal effect on cognitive control, we need to examine L2 acquisition. Furthermore, to examine how the effects of bilingual processing may ripple out to other cognitive processes, we need to understand what cognitive control systems L2 processing brings online and how these control systems operate in the context of L2 use. To begin to address these questions, we must first have an understanding of the L2 acquisition process, as well as the neural systems underlying cognitive control. The following sections will summarize some of the relevant models in the L2 acquisition and cognitive control literatures, before returning to my primary questions of interest.

Developmental Models of L2 Acquisition

One of the formative models in the field of L2 acquisition is the Revised Hierarchical Model (RHM; Kroll & Stewart, 1994). This model, which describes L2 word processing in adult L2 learners, suggests that when learners use their L2, they initially access concepts through their L1. This detour is due to the strong pre-existing connections between the L1 word form and the concept, as well as the connection between the L2 word form and the L1 word form, which is strengthened through typical classroom translation-style teaching. As learners gain in proficiency however, the model suggests that they develop and strengthen the relationship between the L2 word form and the associated concept, such that they no longer need to detour through the L1 when using the L2.

Later models, such as the developmental variant of the Bilingual Interactive Activation model (hereafter, BIA-d; Grainger, Midgley & Holcomb, 2010) and the Modified Hierarchical Model (Pavlenko, 2009) have added to the framework initially established by the RHM. The Modified Hierarchical Model, for example, allows for the possibility of both language-shared and language-specific elements in the conceptual store, which was in its original form entirely shared. This allows for the model to better account for existing lexical categorization data, which suggests that although bilinguals' patterns of lexical categorization tend to converge across their languages, they also maintain some language-specific distinctions (Ameel, Malt, Storms & Van Assche, 2009).

In contrast, the BIA-d focuses on the nature of the connections at the form level, rather than the conceptual level. The major change that this model adds to the RHM is the addition of inhibitory connections between L1 and L2 forms after these forms have established their own connections to the conceptual store. The addition of inhibition is driven by the predictions of the original Bilingual Interactive Activation (BIA) model (Dijkstra & Van Heuven, 1998), which is a model of bilingual word reading. The BIA model operates on the principle that word reading in languages with shared orthography can activate whole-word orthographic representations from both languages. Consequently, the model includes a mechanism for top-down inhibitory control that allows for the selection of the correct language. In the case of the BIA-d, these inhibitory connections add the ability for this model, unlike the original RHM, to account for findings in the priming literature which do not find priming in the L2 to L1 direction, as would be suggested by the RHM's hypothesis that L2 and L1 forms share highly excitatory connections (Grainger et al., 2010).

In addition to the BIA-d, whose predictions are based primarily on the behavioral L2 and bilingualism literature, other models such as the Convergence Hypothesis (hereafter CH; Green, 2003) have incorporated inhibition into its predictions based on the findings of the L2 neuroimaging literature. The CH suggests that while L2 learners may initially draw on extended resources when processing their L2, with increasing proficiency their processing will converge with the resources used in L1 processing. With regard to inhibition specifically, Abutalebi (2008) summarized the findings of the L2 acquisition literature, describing a pattern of increased cognitive control recruitment in L2 learners compared with proficient bilinguals. These areas specifically included the prefrontal cortex (PFC), anterior cingulate cortex (ACC), inferior parietal lobe (IPL) and the caudate nucleus (CN). The following section will review the function of these areas within the cognitive control network, before describing their specific roles within models of cognitive control and L2 acquisition.

Neural Basis of Cognitive Control

Cognitive control draws on a large network of brain regions, and the role that each region plays is still an active area of research. Abutalebi's (2008) characterization of the prefrontal cortex, for example, misses some of the subtleties associated with different areas of the PFC. That is, the PFC can be divided into several different anatomically defined regions, including the inferior, middle, and superior gyri (henceforth IFG, MFG, and SFG, respectively; sometimes the latter two are grouped together in the literature as the dorsolateral or DLPFC), and medial PFC. While both the IFG and SFG are often associated with active inhibitory control, research by Rizio & Dennis (2013) suggests that the IFG is more associated with motor inhibition, whereas the SFG is more associated with cognitive (i.e., memory) inhibition. There are also lateralization differences, where the left IFG is often implicated in lexical selection as well as inhibitory control, and the right IFG is more often implicated in non-linguistic control, both inhibitory and attentional (Bari & Robbins, 2013; Van Heuven, Schriefers, Dijkstra & Hagoort, 2008). Even within the IFG itself, research suggests that it is organized along a rostral-caudal gradient, such that more abstract (e.g. syntactic rule) processing is associated with activity in rostral areas such as pars orbitalis, while less abstract (e.g. stimulus-response) processing is associated with activity in pars opercularis and pars triangularis (Uddén & Bahlmann, 2012).

The medial PFC and its close neighbor, the ACC, are also commonly activated in response to cognitive control tasks. Rather than being associated with inhibition, however, these regions are typically implicated in integration (Yarkoni, Speer & Zacks, 2008) and monitoring (Abutalebi & Green, 2008), respectively. Medial PFC is part of the default mode network, which is characterized by becoming less active when during activity than at rest (Raichle et al., 2001). Similarly, medial PFC reflects ease of processing in language as it becomes more active when participants are presented with coherent, rather than incoherent sentences, or when sentences are preceded by a congruent, rather than incongruent, cue (Diaz & Hogstrom, 2011; Ferstl, Neumann, Bogler & von Cramon, 2008). The ACC also monitors and responds to conflict, and is thought to then elicit activity in lateral prefrontal areas such as the IFG and DLPFC (Egner & Hirsch, 2005; Niendam et al., 2012).

Another area that is thought to signal the PFC is the inferior parietal lobe, or IPL, which has been implicated in studies of inhibition, working memory, and cognitive flexibility, as well as language processing (Binder & Desai, 2011; Niendam et al., 2012). Within inhibition, the IPL is considered to specifically contribute to automatic inhibition triggered by stimulus-response mappings (Spierer, Chavan & Manuel, 2013). These varied roles are at least partially anatomically divided. Uddin et al. (2010) examined the connectivity of the IPL as divided into five parts: an anterior and posterior aspect of the angular gyrus (AG) and three sub-areas within the intraparietal sulcus. For this review, their analyses of the AG are most pertinent. They found that the posterior AG was functionally and structurally linked to areas in the default mode network (a network of regions that is more active at rest than when performing a task, see Raichle et al., 2001), including the medial prefrontal cortex, posterior cingulate, precuneus, and hippocampus. In contrast, they found that the anterior aspect of the AG was connected to the basal ganglia, ventral premotor areas, and the ventrolateral prefrontal cortex, including the inferior frontal gyrus. Consequently, they suggest that this aspect of the AG is particularly involved in both language processing and cognitive control.

To date, the information flow among these regions during control task performance is thought to occur in the following order: the AG and prefrontal cortex signal the basal ganglia, which then projects to the thalamus and ultimately motor cortex (Braunlich & Seger, 2013;

Spierer et al., 2013). Given their integral role in response cuing, it is important to also discuss the basal ganglia. The basal ganglia can be further subdivided into the striatum (consisting of the caudate nucleus and putamen), globus pallidus, subthalamic nucleus and substantia nigra. The basal ganglia are extensively connected with the cortex, and each of its nuclei play distinct roles. The head of the caudate nucleus, for example, is often associated with cognitive control, while the putamen is more typically activated when movement is required (Braunlich & Seger, 2013). Understanding the general functions of each of these players in the cognitive control network allows us to begin to build theories of cognitive control processing, as described in the following section.

Theories of Cognitive Control. Taken as a whole, the preceding studies support the idea that cognitive control processing shares resources with L2 acquisition, although much remains to be understood about the nature of this relationship. In this respect it may be helpful to re-examine these data not through the lens of current psycho-linguistic theories, but rather through current theories of cognitive control. The following sections will introduce cognitive control theories both generally and as they have been specifically applied to bilinguals.

General Cognitive Control Theories. A recent model of cognitive control[1] put forth by Verbruggen, McLaren and Chambers (2014) suggests that cognitive control requires a minimum of three sub-processes: detection, selection, and execution. Signal detection requires a balance between selective attention and change detection, and the authors suggest that dorsal and ventral frontoparietal attention networks may mediate this balance. Dorsal attention networks are thought to be involved primarily in selective attention and the detection of salient stimuli, while ventral networks allow for reorientation from one stimulus to another. Signal selection and

[1] Their theory specifically attempts to circumvent the use of the term inhibition, which the authors call a homunculus.

execution in their model also rely heavily on the role of attention; Verbruggen et al. suggest that selective attention has the ability to resolve the competition involved at each stage by biasing information or features of the stimuli.

Most relevant to our discussion of bilingualism, however, are the authors' predictions concerning automaticity in control processing. Although the idea that stimulus-response associations can become automatized is certainly not new, research by Verbruggen and colleagues has supported the idea that this automatization process can apply to complex, as well as simple, associations. They have shown that pairing a stimulus with a stop response significantly slows later responses to that stimulus (Verbruggen & Logan, 2009), and studies in the task-switching literature have shown that individual stimuli can become associated with higher-order task representations (e.g., Koch & Allport, 2006). Consequently, Verbruggen et al. (2014) argue that rule-based cognitive control, in addition to simple stimulus-response mappings, can also become automatized.

Verbruggen et al.'s (2014) theory describes cognitive control generally and defines it as: "the functions of the cognitive system that allow people to regulate their behavior according to higher order goals or plans" (p. 497). Other theories of cognitive control take a more narrow view, such as the one put forward by Spierer, Chavan and Manuel (2013). Their summary of the neural correlates of cognitive control refers specifically to inhibitory control, which they define as "the ability to suppress ongoing or planned motor or cognitive processes" (p.1). Although their focus was more narrow, Spierer et al.'s (2013) refer to distinctions previously developed by Verbruggen & Logan (2009).

Specifically, their review focused on how different training regimens may differentially affect the types of cognitive control that are strengthened: either automatic (bottom-up) or controlled (top-down). Specifically, they suggest that training regimens with consistent stimulus-response pairings, such as the Go/No-go task (where participants respond to one type of stimulus but not another) are likely to strengthen automatic inhibitory responses to those stimuli, while training regimens with inconsistent stimulus-response pairings, such as the Stop-Signal task (where participants respond to all stimuli unless the stimulus is followed by a stop signal) tend to strengthen top-down inhibitory processes. They further note that top-down inhibitory processes are slower and usually involve the IFG, while bottom-up inhibitory control processes are faster and involve direct connections from the parietal cortex to the basal ganglia. Training on each these processes results in decreased activity in their associated regions of interest (see Manuel, Grivel, Bernasconi, Murray & Spierer, 2010; Manuel, Bernasconi & Spierer, 2013). Their model is summarized in *Figure 1* below:

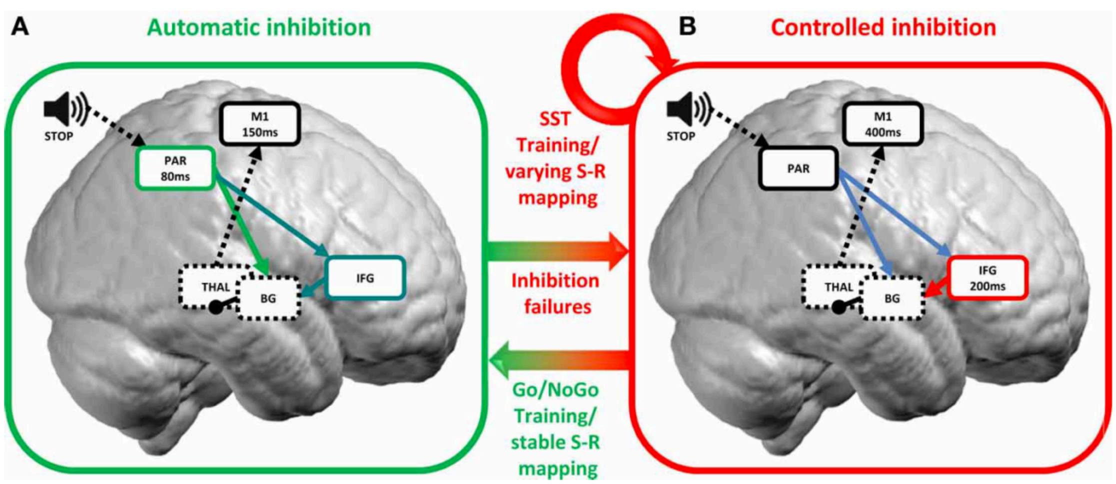

Figure 1. Bottom-up and top-down inhibitory control networks, adapted from Spierer et al., (2013). In side A, signals from the parietal lobe are sent directly to the basal ganglia (green arrow) and from there inhibitory signals are sent to the thalamus, which then directs activity in motor cortex. In side B, signals from the parietal lobe to the basal ganglia are routed through the IFG, causing a delay in the stop response. PAR=parietal lobe, M1=primary motor cortex, THAL=thalamus, BG=Basal Ganglia, IFG=Inferior Frontal Gyrus, SST=Stop-signal task. Arrows indicate excitatory connections and rounded arrows indicate inhibitory connections; full lines indicate cortical connections and dashed lines indicated subcortical connections.

Spierer et al.'s (2013) model shares some, but not all, of the mechanisms of another model of cognitive control developed by Munakata et al. (2011). Their model proposes two mechanisms of inhibition: directed global and indirect competitive. The directed global mechanism is similar to top-down model of control proposed by Spierer et al. (2013) in that it proposes that the PFC is directly responsible for promoting inhibition. Munakata et al.'s (2011) model differs slightly in that they make more specific predictions about the types of cells (GABAergic interneurons) that are responsible for the inhibition of the target region. The other mechanism proposed by Munakata et al., the indirect competitive mode, suggests that exciting connections associated with a particular goal allows for selection of that goal over competitors. This indirect competitive mode, in its emphasis on excitation rather than inhibition, is similar to Verbruggen et al.'s (2014) emphasis on the role of selective attention in signal selection and execution, although the similarity between the two models ends there, as Verbruggen et al. do not describe any processes that would correspond to Munakata et al.'s (2011) directed global inhibition.

Returning to indirect competition, that concept is also shared by another model, the Matched Filter hypothesis (Chrysikou, Weber, & Thompson-Schill, 2013). What differentiates their model is that it suggests that the application of this mechanism is task dependent, such that optimal performance on explicit, rule-based tasks should require more prefrontal involvement, while implicit, reward-based tasks should not. The distinction that Chrysikou and colleagues draw here is similar to, although not exactly the same as the distinction that Verbruggen et al. (2014) or Spierer et al. (2013) draw between automatic and controlled inhibition. Chrysikou et al. (2013) note that stimulus driven or habitual action should require less PFC involvement, as predicted by Spierer et al. (2013), and Chrysikou and colleagues (2013) suggest that training may be one way in which their proposed filter could be adjusted, but they do not make explicit the connection that Spierer et al. (2013) do, which is that training can alter the activation of networks associated with automatic and controlled inhibition, both inside and outside the PFC.

Cognitive Control in Bilinguals. Although cognitive control has long been its own area of research, it has also been applied to theories of bilingual language processing. One of the first such models was the Inhibitory Control model (Green, 1998). This model posited multiple levels of control, both language-specific in the form of language task schemas, and general, in the form of the supervisory attentional system. Green posited that the language task schema in use by the bilingual would reactively inhibit potential competitors for selection (i.e. inhibit *perro* rather than *dog* when one is speaking to an English monolingual) at the lemma level on the basis of language tasks. Furthermore, the supervisory attentional system is proposed to modulate the language task schema in reference to the intended goal of communication and comes online when the task schema's automatic control is insufficient.

The idea that cognitive control is only recruited when necessary applies also to the Convergence Hypothesis (CH; Green, 2003; Green, Crinion & Price, 2006). As described earlier, this hypothesis suggests that L2 learners should draw on the same general systems for L1 and L2 processing, and that the systems used to process the L2 should more closely resemble those used in L1 processing as L2 proficiency increases. These predictions were applied more specifically to cognitive control by Abutalebi (2008; see p.3 above) and were further refined by Green and Abutalebi (2013) into the Adaptive Control Hypothesis. This hypothesis suggests that control processes may operate differently in bilinguals who engage in different interactional contexts, such as single-language, dual-language, and dense code-switching. As most classroom second language learners operate under a single-language context (i.e. they use their L1 and L2 in distinct environments), a description of the predictions for that context is most pertinent. Green and Abutalebi suggest that bilinguals who operate primarily in a single-language context should draw primarily upon resources associated with conflict monitoring, interference suppression and goal maintenance, subserved by the ACC, left inferior frontal cortex, or IFC, and the parietal cortex, respectively (see *Figure **2***). It is also worth noting that the model hypothesizes a more prominent role for the basal ganglia within dual-language contexts, which is interesting because the basal ganglia have commonly been observed to be active in studies of second language learners (e.g., Abutalebi, 2008), who often learn in primarily single-language environments. This may suggest that experimental studies of second language processing in language learners elicit the dual-language context network, which is more widespread and includes right IFC, the thalamus and the cerebellum in addition to the basal ganglia.

Beyond merely identifying critical regions during each pattern of language use, the Adaptive Control model also makes predictions about the functional connectivity between these regions (see *Figure **2***). Another model of bilingual language control, the Conditional Routing model, also places importance on the role of connectivity during language processing (Stocco, Yamasaki, Natalenko & Prat, 2014).

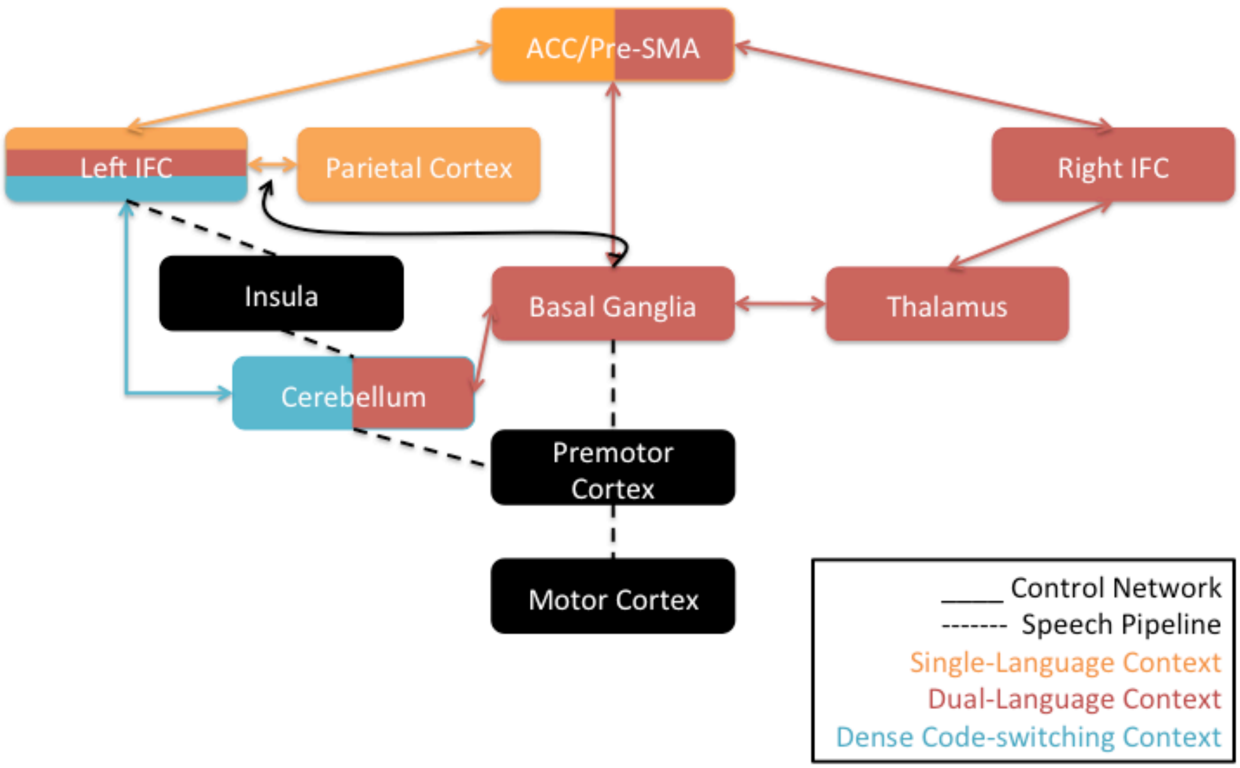

Figure 2. Regions of Interest and Connectivity in The Adaptive Control Model. Activity flows from top to bottom, resulting in speech output. ACC=Anterior Cingulate Cortex. Pre-SMA=Pre-Supplementary Motor Area. IFC=Inferior Frontal Cortex.

In contrast to the predictions of the Adaptive Control hypothesis, the Conditional Routing (CR) model (Stocco et al., 2014) predicts that bilingual experience (they do not specify interaction type) trains the basal ganglia rather than the cortex. The CR model builds on literature that proposes that the basal ganglia have the ability to modify the strength of cortico-cortical connections (see Stocco, Lebiere & Anderson, 2010).

Stocco and colleagues (2014) suggest that bilingual experience, with its recurrent requirements to inhibit the language not in use and excite the required language, provides extensive practice and consequently improved efficiency at this conditional routing process, which is necessary not only during bilingual speech but also during situations requiring non-linguistic executive control, such as task-switching. Stocco's conditional routing shares characteristics with Munakata et al.'s (2011) proposed indirect competitive mode, where enhanced processing of connections associated with a goal allows for the selection of that goal compared to competitors. An interesting difference between Stocco et al.'s (2014) model and the more general model that Munakata et al. (2011) put forth is that Munakata et al. suggests that the PFC modulates excitatory activity, rather than the basal ganglia as Stocco et al. (2014) suggest.

Cognitive Control as a Network. The literature reviewed above suggests that both in general models of control and those applied to bilingual language processing, taking a network perspective has become increasingly important (see Li & Grant, 2015). Work by Yang, Gates, Molenaar and Li (2015), for example, has shown that connectivity patterns differ between more and less successful learners, both before and after language training. Consequently it is worth taking some time to consider the different network perspectives espoused by these models and the similarities and differences therein.

One commonality across the models from Green and Abutalebi (2013), Stocco et al. (2014), Spierer et al. (2013) and Munakata et al. (2011) is that they all emphasize the relationship between the prefrontal cortex and the basal ganglia. Spierer et al. (2013) and Munakata et al.'s (2011) models propose unidirectional influence from the PFC to the basal ganglia, while the Conditional Routing (Stocco et al., 2014) and Adaptive Control (Green & Abutalebi, 2013) models both suggest that the basal ganglia either unidirectionally or bidirectionally, respectively, affect cortico-cortical connections with the PFC. The differentiation between the linguistic and non-linguistic models and their proposed directional influence between the PFC and basal ganglia is interesting, and can be tested directly using directed functional connectivity modeling approaches such as Group Iterative Multiple Model Estimation (GIMME; Gates & Molenaar, 2012). Most likely is that the system is actually a loop (e.g., Braunlich & Seger, 2013) and the aforementioned models are concentrating on information flow in one direction or the other. If this is the case, that distinction should be made clearer in those models in order to better understand the relationship between functional connectivity and performance.

Another similarity across the models is that they each address the issue of automatization, with the exception of Munakata et al. (2011). Spierer et al. (2013) is the most explicit of the three, making the claim that the difference between controlled and automatic processing hinges on the involvement of the PFC: automatic processing proceeds from parietal attentional regions directly to the basal ganglia, while controlled processing is routed through the PFC first. In contrast, the Conditional Routing model (Stocco et al., 2014) suggests that the basal ganglia are the key players, such that more complex, rule-based processing must be routed through the basal ganglia while simpler or more automatic processing is able to be processed primarily via cortico-cortical connections. The Adaptive Control model makes similar predictions, although they use different terminology. Green and Abutalebi suggest that language processing in a single-language context (i.e., simpler) can be processed primarily via cortico-cortical connections, with the exception of the ACC. In dual-language contexts (i.e., more complex, involving more switching), they predict that subcortical regions, including but not limited to the basal ganglia, will be more important.

From these models it is clear that although there is an emerging consensus regarding the neural bases of cognitive control, much remains to be understood. For example, although models of bilingual language use share the distinction between automatic and controlled processing, these models do not devote much time to the elaboration of this distinction, and do not describe how controlled processing may become automatic. For this, it is necessary to refer to models in the general cognitive control literature, such as Spierer et al. (2013), who make clear, testable predictions concerning the mechanisms of cognitive control automatization.

From the above review of bilingual and general cognitive control theories we may draw two generalizations. One, that bilingualism and cognitive control draw on similar brain networks, and the experience of bilingualism may act as a type of training to affect how cognitive control is executed in the brain. Two, this type of training may be similar to the process of automatization in cognitive control, and is characterized by a decreased reliance on prefrontal cognitive control mechanisms. In the following sections, I will review the current literature on cognitive control and language processing as well as the emerging literature in language training, with a focus on the inter-relatedness of language and cognitive control.

The Role of Cognitive Control Regions in Language Processing

As discussed above, many of the regions involved in cognitive control are activated during language processing. Parker Jones et al. (2011) demonstrated this particularly well in a clever paradigm that managed to tease apart the processes involved in picture naming, word reading, articulation, word recognition, semantic processing and perceptual processing. Both bilinguals and monolinguals completed all the tasks in a single language, and yet bilinguals were found to have higher activation than monolinguals in the following areas during the language (naming, reading aloud, and semantic decision) tasks: precentral gyrus (part of DLPFC), planum temporale (part of the superior temporal gyrus adjacent to the IPL), superior temporal gyrus (STG), pars opercularis (part of IFG), and pars triangularis (part of IFG) extending into the insula. The latter two areas were more sensitive to naming and reading aloud than simply articulating, while the first three areas did not differ significantly across the three tasks. The authors interpret the higher activation in bilinguals as resulting from the increased competition bilinguals experience during lexical selection. Consequently, this study exemplifies how cognitive control is recruited more by bilinguals than monolinguals during purely linguistic tasks.

The bilinguals in Parker Jones et al.'s (2011) study, however, were all highly proficient in both of their languages. How proficiency interacts with the use of cognitive control is a more complicated question. The following studies have used varying methodologies to address this question; I begin with the functional MRI studies that are most directly comparable to Parker Jones et al. (2011). Yang et al. (2015) scanned participants while they completed tone discrimination, pitch discrimination, onset discrimination, and word-picture association tasks, both before and after training on Mandarin vocabulary. They found that more successful learners showed higher activation in the IFG, insula, lingual gyrus and cuneus, similar to Parker Jones et al. (2011). In their functional connectivity analysis of the tone discrimination task, they found that the more successful learners had more highly integrated functional networks even before training. These pre-training networks included connections between areas associated with cognitive control such as the MFG, IFG, and IPL. These results suggest that learners' use of the cognitive control system may contribute to their L2 learning success.

Results from a structural imaging study by Mårtensson et al. (2012) support this interpretation. In their study they found that participants who spent three months in an intensive interpreting program showed significantly more cortical thickness in the MFG, IFG, and STG, as well as increased hippocampal volume, in comparison with controls. Furthermore, they observed a positive correlation between thickness in the MFG and learning "struggle" as measured by instructor evaluations. These results in conjunction with those of Yang et al. (2015) emphasize the role of cognitive control in language learning. The nature of this role and how it changes over time, however, remains to be determined.

A series of longitudinal studies by Stein et al. (2006; 2009) has shed some light on this issue. Using both EEG and fMRI techniques, Stein and colleagues have observed that after five months of immersion experience in their second language, L2 learners display significantly less activity in the IFG while completing a semantic decision task. This finding was initially observed via source localization of EEG data, and was then replicated using fMRI. In fact, BOLD activity in bilateral IFG decreased between the two sessions such that at the second session only the left IFG remained significantly more active to L2 words than L1 words. Interestingly Stein and colleagues did not observe differences in other areas of the control network (e.g., basal ganglia, inferior parietal lobe), but this may be due to their relatively small number of subjects: 12 in the EEG study and 10 in the fMRI study.

The small number of participants in Stein's work is a clear artifact of the difficulty of carrying out longitudinal work with second language learners, which can be a difficult population to recruit. One way of circumventing this problem is by creating one's own pool of second language learners through the use of miniature languages and training studies (e.g., Morgan-Short, Sanz, Steinhauer & Ullman, 2010), with the added benefit of random assignment to condition, thereby removing the possibility of self-selection effects. The following section will review the current literature on language and cognitive control training in order to better understand the relationship between these two domains.

Effects of Training on Cognitive Control and Language Processing

As noted in the section on cognitive control theories (p. 6), cognitive control automatization is thought to co-occur with decreased activity in its associated regions (e.g. PFC, parietal cortex). To understand how this decrease is implemented, and what aspects of cognitive control it is associated with, require studies of cognitive control training. One such study was conducted by Berkman, Kahn and Merchant (2014), who examined the neural correlates of training on the Stop-Signal task (hereafter, SST). They trained participants on either the SST or a control two-alternative forced-choice task for three weeks, with a total of approximately 1 hour of training between the initial scan and the final scan. Berkman and colleagues found that participants improved significantly in performance on the SST from the beginning to the end of the training. With respect to the neural correlates of inhibition, they noted that activity in the IFG decreased significantly during the implementation of the stop response from the beginning to the end of the training, although its activity increased during the cues that preceded training. Furthermore, performance on the task correlated with increased activity in the MFG during presentation of the cue and decreased activity in MFG during stop implementation. These results are congruent with the directed global method of inhibition proposed by Munakata et al. (2012) and the top-down model of cognitive control put forward by Spierer et al. (2013), which is in turn consistent with the idea that the SST stresses top-down control in particular (Spierer et al., 2013; Verbruggen & Logan, 2009).

In addition to being sensitive to task differences, research on cognitive control training has also found that individual differences in factors such as age influence activation patterns. Braver, Paxton, Locke and Barche (2009), for example, found that when younger and older adults performed a cognitive control task (the AX version of the Continuous Performance Test, or AX-CPT) younger adults tended to show more activation in response to cues, while older adults tended to show more activation in response to probes. These two activation patterns correspond to proactive and reactive control, respectively. Interestingly, however, the effect of age can be reversed via training. In this case, older adults received strategy training on the AX-CPT, while younger adults completed a penalty incentive version of the task that drew additional attention to the probe. Under these conditions, older adults showed increased activity to cues, and younger adults to probes, in the same cognitive control regions: bilateral MFG, IFG, and supplementary/premotor cortex. These results are indicative of cognitive control training's potential to influence both the brain and cognition.

Further supporting the hypothesized effect of cognitive control training on the brain are data from structural imaging studies. Takeuchi et al. (2010), for example, showed increased white matter integrity in areas underlying the intraparietal sulcus and anterior corpus callosum following two months of cognitive control training. Their participants completed approximately 25 minutes of training per day on three different tasks: a spatial working memory task, an operational N-back task, and a dual N-back task. Interestingly, the areas showing increased FA in this study, the intraparietal sulcus and the anterior corpus callosum, also were shown to be better preserved in bilinguals as compared to monolinguals by Luk, Bialystok, Craik and Grady (2011). Such an overlap in effects suggests that cognitive control training and bilingualism may have similar effects on the brain, and consequently that training in one domain may affect performance in the other.

Few studies, however, have examined the effect of language training on executive control skills. Zhang, Kang, Wu, Ma, and Guo (2015) tested Chinese-English bilinguals on the AX-CPT both before and after language-switching training. They found that language-switching training resulted in a switch towards proactive control, both behaviorally and as measured by the amplitude of the N2 component elicited by the cue. Neither of these results was observed in a control group who did not undergo language training. Perhaps even more surprising than Zhang et al.'s results are those reported by Sullivan et al. (2014). Sullivan et al. studied L2 learners of Spanish and a control group of students enrolled in Introductory Psychology for six months, testing both their behavioral and event-related potential (ERP) responses to the GNG task and a sentence judgment task before and after language training. Although there were no differences between the groups behaviorally, their ERPs differed significantly after training. Specifically, only the language-training group showed an increase in P3 amplitude on the GNG task and decreased P600 amplitude on the sentence judgment task. In addition, the size of the P3 increase was positively correlated with participants' grades in their Spanish course. Their results suggest that language learning affects how our brain processes both language and cognitive control tasks, even if these effects are not obvious behaviorally (see also Ramos et al., 2016).

Training in the opposite direction, (i.e., examining the effect of cognitive control training on language processing) also appears to be effective, although the literature so far has concentrated on the effects of training on L1 processing. Novick, Hussey, Teubner-Rhodes, Harbison and Bunting (2014) found that three weeks of training on the n-back task led to improvement in recovery from garden-path sentences. Specifically, they trained participants on a version of the n-back task with lures. For example, in a typical 3-back task H-B-K-H, the second H would be a target; in a lured condition, the second H of the sequence H-B-H-D would be a lure because it appears one space away from the target position. They also trained participants on a letter-number-sequencing task (where participants must re-order and remember a sequence of letters and numbers), a running span task (where participants had to listen to a stream of 12-20 items and recall the last *n* items when the stream ended), and a block span task (a test of visuo-spatial working memory). Participants were trained on all four tasks for approximately 15 minutes each across 20 sessions which occurred in a three to six week period between pre-test and post-test. A multiple regression analysis revealed that only performance on the n-back task significantly predicted improvement in the processing of syntactically ambiguous sentences. These data suggest certain aspects of language processing rely on domain general executive function skills, and furthermore show that training on these executive functions can impact language processing.

To review, the evidence to date appears to indicate that training studies can significantly influence both patterns of brain activity and behavioral outcomes. Furthermore, these effects appear to extend beyond the specific training domain, from language processing to cognitive control and cognitive control to language processing. Such spillover is predicted by current theories of bilingual language processing (e.g., the conditional routing model; Stocco et al., 2014) but models of L2 lexical development do not all agree on when cognitive control is most critical to the learner (e.g. the BIA-d and the CH; Grainger et al., 2010; Green, 2003). The discrepancies between these two positions (i.e., cognitive control is critical during early L2 acquisition vs. cognitive control is critical for effortless access to L2 representations by advanced learners) may be explained by current models of cognitive control, which suggest that control can be thought of in two ways: as a slow, controlled, top-down process and as a stimulus-driven, automatized, bottom-up process (Spierer et al., 2013; Verbruggen et al., 2014). The current study will attempt to address these outstanding questions by examining: a) the neural correlates of L2 semantic processing and its shared substrates with cognitive control and b) how control training may influence L2 semantic processing.

Current Study

The current study is composed of two experiments, which each correspond to a different goal. My first goal was to identify the neural substrates shared between L2 processing and cognitive control, in both the bottom-up and top-down directions. The second was to investigate if L2 processing is sensitive to cognitive control training. The following sections will preview the experiments designed to achieve each goal.

Experiment 1. This experiment was motivated by the abovementioned literature, as well as the results of my Master's work, which examined the neural correlates of L2 and L1 processing in a language decision task (Grant, Fang, & Li, 2015). Of the regions that were more active for the L2 than the L1, we found that many ROIs associated with cognitive control such as the ACC and caudate nucleus (CN) decreased in activity with increased L2 experience, but some such as the MFG and IFG increased. This pattern was partly congruent with the CH, but also partly congruent with the BIA-d model. The first goal of these experiments (to identify the neural substrates shared between L2 processing and each type of control) was motivated by those data in the hopes of better differentiating the predictions of the CH (Green, 2003) and BIA-d (Grainger et al., 2010) models.

Previous work by Branzi, Della Rosa, Canini, Costa, and Abutalebi (2016) has also compared the neural correlates of language and non-linguistic control, although without considering the role of proficiency (their participants were a set of highly proficient German/Italian bilinguals), or different types of cognitive control. Nonetheless, their data suggest that highly proficient bilinguals rely on both the LIFG pars triangularis and LIPL when exerting language and non-linguistic control (during naming and size judgments, respectively). Although the authors did not interpret their data with respect to the difference between top-down and bottom-up control, these results support the hypothesis that bottom-up control is recruited by highly proficient bilinguals, as both the IFG pars triangularis and IPL have been previously implicated in bottom-up control (Lenartowicz et al., 2011; Manuel et al., 2010). My study builds on these data by not only examining the role of learner proficiency, but also explicitly testing bottom-up and top-down control through the use of the Go/No-go (GNG) and Stop-signal (SST) tasks.

The inclusion of proficiency as a variable is crucial, as it may illuminate the relationship between individual differences in cognitive control (generally measured as top-down control) and language learning success. That is, if language learning relies on different types of control at different points in the learning process, then we could potentially predict the influence of individual differences in control at various stages of learning. Specifically, one might predict that individual differences in top-down control processing would be most predictive of early learning success.

To assess these questions, I used multiple analysis techniques in order to arrive at a more comprehensive and nuanced understanding of the data. Like in Grant et al., (2015), I used univariate and directed functional connectivity analyses to evaluate the overall activity and the connections between them, which are directly relevant to theories such as the CH/BIA-d (Grainger et al., 2010; Green, 2003) and Adaptive Control/Conditional Routing hypotheses (Green & Abutalebi, 2013; Stocco et al., 2014). Additionally I used a multivariate analysis approach to assess more subtle changes in the pattern of activity within regions, as opposed to the overall activity that mass univariate analyses describe. These analyses provide complementary data that identify regions where activity patterns are more similar within one group than another (as opposed to more or less active) and can provide a new perspective on the

CH's claim that L2 learners' brain activity patterns come to converge with that of the L1 (Green, 2003).

Experiment 2. For all the strengths of the neuroimaging analyses of Experiment 1, they remain correlational. In an attempt to evaluate if there are causal relationships between control and L2 processing, the second experiment examined the effects of top-down, bottom-up, and sham training on L2 acquisition. I predicted that the top-down training would be the only condition to affect L2 acquisition, as bottom-up training relies on the creation of specific stimulus-response associations. Such a pattern of results would support current literature that suggests that even moderate proficiency in a second language may result in lasting effects on other areas of cognition, because the initial acquisition process for adult learners should rely primarily on the more transferable process of top-down control (Ljungberg, Hansson, Andrés, Josefsson, & Nilsson, 2013).

Together, these experiments allowed me to assess the relationship between cognitive control and L2 acquisition in terms of their shared neural correlates and the causal nature of the relationship.

Chapter 2: L2 Proficiency and the Direction of Control

If we assume that lexical processing in the L2 involves mapping new forms onto the same conceptual representations associated with the L1, this inherently creates an inconsistent mapping situation that requires top-down control (for further details concerning mapping consistency between L1 and L2, see Van Hell & De Groot, 1998). The degree of top-down control required is likely affected by the frequency of L2 to concept access (and consequently the strength of the direct connection between the L2 form and its concept), which one could argue corresponds with L2 proficiency. The idea that increases in L2 proficiency lead to decreases in the amount of top-down control required is consistent with the extant neuroimaging evidence (e.g. Abutalebi & Green, 2008). However, what has not been discussed in the L2 literature is that as learners receptively and productively strengthen the mapping between the L2 form and its concept through increased L2 use, the use of cognitive control does not disappear. As indicated by studies of simultaneous and highly proficient bilinguals, both languages of the bilingual are active at any given time, and consequently even highly proficient bilinguals require a mechanism to mediate lexical selection between the two languages (Kroll, Bobb, & Wodniecka, 2006; Marian, Spivey & Hirsch, 2003; Van Heuven, Dijkstra, & Grainger, 1998). Consequently, what is more probable than a complete disappearance of control is a change in the type of control that is engaged during L2 processing: from top-down to bottom-up. The fast, automatic process of bottom-up control better fits Grainger et al.'s (2010) description of inhibition as facilitating L2 production in proficient learners, even though their proposed model was based on the top-down inhibition described by the original BIA.

Consequently, Experiment 1 examines the influence of L2 proficiency and mapping consistency (as manipulated by the use of language ambiguous and unambiguous stimuli) on the use of control by L2 learners. If bottom-up control does increase with proficiency, I expected to see more activation in the parietal-putamen motor loop, rather than the IFG-CN executive control loop, for higher proficiency learners (Braunlich & Seger, 2013). This hypothesis is based on the findings by Manuel et al. (2010) that suggest that training on bottom-up control tasks affects regions traditionally associated with motor, rather than cognitive, control.

It is possible, however, that the IFG may also be involved in bottom-up control, as a previous study by Lenartowicz, Verbruggen, Logan and Poldrack (2011) found that the IFG was active in response to stimuli previously associated with stopping, even when a stop response was not required. Their findings are consistent with Rizio and Dennis (2013), who found that the IFG was more associated with motor, rather than cognitive, inhibition. The conflicting predictions regarding the role of the IFG may be due to the size of the region, which is hypothesized to be organized according to a rostral-caudal gradient (Uddén & Bahlmann, 2012). Consequently, I expected that if I observed greater/equivalent activity for highly proficient learners in the IFG, as Lenartowicz et al. (2011) did, I would find it in pars triangularis. This would replicate Lenartowicz et al.'s results, and would also be congruent with the cognitive control theory put forward by Uddén and Bahlmann (2012). Investigating these two types of control processing using fMRI allows me to integrate the literature investigating bottom-up and top-down control with the rostro-caudal gradient of control, which previous studies using ERP (e.g. Manuel et al., 2010) have been unable to do.

Method

Participants. Participants in this study were 40 native English speakers enrolled in Spanish classes. Two participants were dropped for failing to meet the inclusion criteria (native English speaker, right handed), one for not completing the experimental task, and four for excessive movement (>3mm). The final sample included 18 low proficient students recruited from Spanish 002-100, and 15 high proficient students recruited from Spanish 300 and above. The average age of the participants was 19.75, and 26 were female. Both the high and low proficiency groups were approximately 80% female (12/15 and 14/18, respectively). High proficiency participants were slightly but significantly older than low proficiency participants (M=20.60 vs. M=19.28; t=2.21, p=.035). All participants were compensated for their time, either monetarily or with course credit when applicable.

Materials. To measure L2 proficiency, I utilized several tools, both subjective and objective: a language history questionnaire, verbal fluency task, semantic decision task, and post-experiment questionnaire. In addition to measures of proficiency, I also took several measures of participants' cognitive control skills, including the AX-CPT, SST, and GNG tasks.

Proficiency Tasks.

Language history questionnaire. The language history questionnaire (LHQ; Li, Zhang, Tsai & Puls, 2014) collects basic information about participants' age, gender, and education, as well as assessing participants' self-rated L2 proficiency, which was used as a covariate in the fMRI analyses.

Verbal fluency task. Results from the category verbal fluency task served as an objective measure of fluency with which to compare their self-ratings and was used as a covariate in the analyses. Specifically, this task requires that participants list as many unique words as possible from a particular category (e.g., animals, fruits, furniture, clothing) within one minute. A native Spanish speaker scored the participants' performance, and the total sum of words produced across all four tasks was used as the covariate for each participant in the fMRI analyses.

Semantic decision task. In this task, which participants completed while in the scanner, participants were presented with three types of words: unambiguous L2 and L1 words and L2 homographs, which share form but not meaning across the participants' two languages (see Appendix A: Stimuli in the Semantic Decision Task for a complete list). Stimuli for the semantic decision task were chosen from the Spanish 002 textbook, *Mosaicos*. Data from the LexEsp corpus indicated that the unambiguous Spanish and Spanish homograph stimuli were not significantly different in length (*M*=70, *SD*=118.91; *M*=42, *SD*=53.97) or frequency (*M*=6, *SD*=1.87; *M*=6, *SD*=2.09).

For each of the 144 trials, participants were asked to identify if the word was bigger or smaller than a shoebox. There were 48 trials per condition, but due to the limited number of appropriate homographs, each condition had only 24 unique stimuli. To increase power, each word type was presented singly in its own block. Within a block six words were presented for two seconds each, with a one second inter-trial interval for a total length of 18 seconds. Between each task block was a fixation block, which lasted for 20 seconds. Block types were mixed within a run. Specifically, each of the four runs had six blocks, two of each word type, and runs three and four repeated the stimuli from runs one and two, although in a new randomized order.

Post-experiment questionnaire. After the scanner tasks participants completed a multiple-choice questionnaire asking them to identify the correct English translation of the previously presented Spanish and homograph words.

Control Tasks.

AX-Continuous Performance Task. The AX-CPT asks participants to respond to a series of letters according to a set of rules. The letters appear in a sequence of five, where the first and last letters are red, and the intermediary letters are white. Participants are instructed to always respond “No” to the first four letters. For the fifth letter, participants are instructed to press “Yes” if and only if the fifth letter is an X, and the first letter was an A. Consequently the task requires participants to engage two types of control: proactive and reactive inhibition. Specifically, reaction times on AY trials measure reactive control, or the participants’ ability to inhibit the “Yes” response based on the earlier “A” cue. The reaction time on the BX trials measures proactive control, or the ability to inhibit the “Yes” response to the current “X” probe based on the knowledge of the earlier “B” cue. The proportion of each trial type (70% AX, 10% AY, 10% BX, and 10% BY) is distributed in order to maximize the inhibition required.

Go/No-go task. As mentioned above, the Go/No-go (hereafter, GNG) task measures inhibitory control by asking participants to respond to certain trial types (e.g. 0000s presented in green) and inhibit responses to another trial type (e.g. 0000s presented in red). Participants completed three runs of the GNG task. Each run was approximately 4 minutes long, and included 40 Go trials and 10 No-go trials. The inter-trial interval was jittered between 2 and 5 seconds. Several behavioral measures can be assessed from this task, including the proportion of incorrect go trials (responses to a No-go stimulus) as well as switch costs, or the RT to Go trials following No-go trials as compared with Go trials.

Stop-Signal task. These same measures can be obtained from the SST task. The SST asks participants to respond to all stimuli, unless that stimulus is followed by a Stop signal (e.g. a change in the color of the text from green to red). The delay between the stimulus and the stop signal determines the difficulty of the task, and while all participants start at the same delay (200ms), their performance determines the length of future trials using a staircase procedure to stay at maximum difficulty for the participant. Specifically, if a participant successfully inhibits their response, then on the next trial the stop signal will be presented 64ms later, whereas if they had incorrectly responded, then the stop signal would be presented 64ms earlier on the next trial. Participants completed three runs of the SST. Each run was approximately four minutes long, and included 40 Go trials and 10 Stop trials. The inter-trial interval was jittered between 2 and 5 seconds.

Procedure. Data for the study was gathered over the course of one 120-minute session. During the first hour participants completed a series of behavioral tasks including the LHQ, L2 verbal fluency task, and the AX-CPT task. Then participants completed the L2 semantic decision task (hereafter, SDT), GNG, and SST in the MRI scanner. After exiting the scanner, participants filled out the post-experiment questionnaire and were debriefed.

MRI Acquisition. MRI images were acquired on a Siemens Magnetom Prisma 3-T MRI scanner at the SLEIC center, using T2*-weighted gradient-echo EPI sequence (TE = 30 ms, TR = 2500ms, flip angle = 90°, FoV = 240 mm, slice thickness= 3 mm, 35 slices). Participants lied supine in the scanner with earplugs and headphones to muffle the noise. They viewed the stimuli through a mirror attached to the head coil, while a tightly fitting vacuum pillow immobilized their heads. For each run, the functional scanning was always preceded by 5s of dummy scans to ensure tissue steady-state magnetization. High-resolution (1 × 1 × 1 mm3) anatomical images were acquired using a T1-weighted, MPRAGE 3D gradient-echo sequence.

fMRI preprocessing and analysis strategy. Preprocessing (motion correction, slice timing, realignment, normalization, and smoothing) was performed using SPM12 (Wellcome Trust Centre for Neuroimaging, University College London; http://www.fil.ion.ucl.ac.uk/spm/software/spm12/). As is common procedure, the first two scans were excluded from data processing to minimize inclusion of images not yet at a steady state.

Functional images were corrected for head motion by aligning all volumes to the middle (17/35) volume using a six-parameter rigid-body transformation. Then, the realigned and re-sliced time-series data were normalized according to the MNI stereotactic space and spatially smoothed by a 6-mm FWHM (full width at half maximum) Gaussian kernel.

For each task, each trial type (SDT: Homograph, unambiguous-English, and unambiguous-Spanish; GNG: Go, Nogo; SST: Go, Stop) was differentiated at the individual level, and t-contrasts were run for each individual. For the SDT, I ran Homograph (H)>Spanish (S) and S>English (E), for the GNG, Go>No-go and No-go>Go, and for the SST, Go>Stop, Stop>Go. The contrasts from the SDT were chosen to isolate the effect of second language processing (S>E) and of cross-language ambiguity (H>S), while the contrasts from the GNG and SST were chosen to isolate the correlates of responding (Go>No-go; Go>Stop) and inhibiting (No-go>Go, Stop>Go) respectively.

Planned analyses. Second level analyses were run to compare the effect of proficiency on each of the contrasts of interest from the SDT. These whole-brain analyses used a regression approach across the entire sample to increase power, and both subjective and objective measures of proficiency were used as regressors. Additionally, whole-brain data from the inhibition contrasts of the GNG and SST tasks were entered into a flexible factorial with data from the contrasts of interest for the SDT. This analysis allowed me to assess via conjunction which regions were activated during both linguistic and non-linguistic control. The WFU pick atlas was used to label the MNI coordinates (Maldjian, Laurienti, Burdette & Kraft, 2003; Maldjian, Laurienti & Burdette, 2004).

Following the whole-brain analyses, analyses were conducted in our a priori regions of interest for the contrasts of interest (H>S; S>E; Nogo>Go; Stop>Go). The ROIs included the three sub-regions of the inferior frontal gyrus (IFG), including orbital frontal cortex (IFG_orb), pars triangularis (IFG_tri), and pars opercularis (IFG_oper), the supplementary motor area (SMA), temporo-parietal junction (TPJ), and the basal ganglia, specifically the caudate nucleus (CN) and putamen (Pu). The WFU pick atlas was used to create the ROI masks and the ROIs were defined using the WFU pick atlas images, then extracted and analyzed using the MarsBar toolbox for SPM12 (Brett, Anton, Valabregue & Poline, 2002; Maldjian et al., 2003; Maldijian et al., 2004). Data from the ROIs were also assessed using the GIMME program, which conducted a uSEM connectivity analysis for both groups on the SDT data (Gates & Molenaar, 2012).

Exploratory analyses. As will be described below, there was an unexpected difference between the two proficiency groups in their AX-CPT performance. This led me to conduct exploratory analyses on the fMRI data for the SDT, GNG, and SST tasks. Specifically, I used independent samples t-tests to assess the affect of proficiency on the GNG and SST fMRI data. I chose this approach rather than a regression approach to best match the difference that I observed in the behavioral AX-CPT data. For the SDT, I included an additional whole-brain analysis using the AY and BX RT data as regressors.

Results

Behavioral.

Language history questionnaire. Data from the LHQ is summarized in Table 1. Participants in the high proficiency groups' average L2 self-rating across the categories of Listening, Speaking, Reading, and Writing was 5.13 (SD=0.67). Participants in the low proficiency groups' average self-rating across the same categories was 4.36 (SD=0.78). The difference between these self-ratings was significant (p=.004; $t(32)$=3.07), suggesting that the participants in the high proficiency group do indeed view themselves as more proficient than those in the low proficiency group.

Table 1. *Language History of the High and Low Proficiency Groups*

Group	LHQ-Listening (SD)	LHQ-Speaking (SD)	LHQ-Reading (SD)	LHQ-Writing (SD)	Verbal Fluency (SD)
High Proficiency	5.07 (.80)	4.73 (.88)	5.47 (.64)	5.27 (.88)	33.4 (7.56)
Low Proficiency	4.37 (.90)	4.11 (.94)	4.58 (.84)	4.37 (.90)	21.89 (6.75)

Verbal Fluency. Performance on the verbal fluency task is also included in Table 1. Overall, the participants in the high proficiency group significantly outperformed those in the low proficiency group (High M=33.4 SD=7.55, Low M=21.89, SD=6.61; p<.001, t(32)=4.73). In addition, Verbal Fluency scores significantly correlated with Self-Rated Proficiency scores (p=.039, R=.355).

AX-CPT. Performance on the AX-CPT is summarized in Table 2. A one-way repeated measures ANOVA examining trial type found that the effect was significant for both Accuracy (p<.001, F(2.47,32)=12.14, η_p^2=.269) and RT data (p<.001, F(2.2,32)=70.253, η_p^2=.68). Pairwise comparisons revealed that for Accuracy, the effect was motivated by significant differences between the AY condition and the other three conditions, which were not significantly different from each other. For RT, the AX condition was significantly faster than the AY condition and slower than the other two conditions, and the AY condition was significantly slower than all other conditions, but the BX and BY conditions did not significantly differ in RT.

In addition to the planned comparisons by trial type, visual inspection of the data suggested that there could be differences in performance between the two proficiency groups. A 2x4 mixed ANOVA revealed that there was a small but significant effect of Proficiency group on Accuracy (p=.009, F(1,32)=7.73, η_p^2=.195), but not RT (p=.803, F(1,32)=0.06, η_p^2=.002) such that the High Proficiency group was slightly more accurate. Follow-up correlations with average Self-Rated Proficiency and Verbal Fluency scores revealed trending relationships between Self-Rated Proficiency and AY accuracy (p=.055, R=.033), and between Verbal Fluency and BX accuracy (p=.088, R=.297).

Table 2. *Performance on the AX-CPT.*

Group	AX		AY		BX		BY	
	ACC	RT	ACC	RT	ACC	RT	ACC	RT
High	.93 (.03)	322 (38)	.75 (.14)	403 (61)	.95 (.04)	241 (52)	.96 (.06)	229 (42)
Low	.88 (.17)	302 (53)	.70 (.23)	386 (70)	.83 (.19)	242 (59)	.89 (.15)	252 (91)
All	.89 (.13)	311 (48)	.72 (.19)	393 (66)	.88 (.15)	242 (55)	.92 (.12)	242 (73)

Notes. RT is presented in milliseconds and standard deviations are provided in parentheses.

Semantic Decision task (SDT). Results from the SDT are provided in Table 3. Mixed 2x3 ANOVAs on the Accuracy and RT data found that there was a main effect of Proficiency for both Accuracy (p=.004, F(1,32)=9.82, η_p^2=.24) and RT (p=.004, F(1,32)=9.427, η_p^2=.23). That is, the High proficiency participants were significantly faster and more accurate than the Low proficiency participants. There was also a main effect of Word Type on both the Accuracy (p<.001, F(2,31)=99.5, η_p^2=.76) and RT (p<.001, F(1.577,31)=29.66, η_p^2=.49, Greenhouse-Geisser corrected) data. Pairwise comparisons of the word types revealed that accuracy on the

English words was significantly higher than on the Homograph or Spanish words (*p*<.001), which were not different from each other (*p*>.05). In addition, English words were responded to significantly faster than Homographs (*p*<.001), which were responded to faster than Spanish words (*p*=.034). In addition, there was a significant interaction between Proficiency Group and Word Type for the Accuracy data (*p*<.001, $F(2,31)=11.8$, $\eta_p^2=.28$) and a trending interaction for the RT data (*p*=.069, $F(1.577,31)=3.03$, $\eta_p^2=.09$, Greenhouse-Geisser corrected). The interaction arises because the High proficiency group is generally more accurate than the Low proficiency group on the Spanish and Homograph words, but not the English words.

Table 3. *Performance on the Semantic Decision Task*

Group	English		Homograph		Spanish	
	ACC	RT	ACC	RT	ACC	RT
High	.94 (.05)	931 (97)	.77 (.09)	1053 (90)	.81 (.10)	994 (88)
Low	.93 (.05)	957 (75)	.70 (.11)	1139 (119)	.64 (.12)	1121 (122)

Go/No-go task. Due to experimenter error, behavioral data for this and the SST task was only collected from 17 participants, 15 of who were included in the fMRI analyses and whose data is reported below. The data available suggests that participants were highly accurate on this task. Accuracy on the Go trials was at ceiling (*M*=.99, *SD*=.04), and accuracy on the Stop trials was also high (*M*=.86, *SD*=.1). The proportion of incorrect go responses, which is equal to 1-Stop trial accuracy, ranged from 0 to 31%. In terms of the RT data, the average Go RT across all trials was 446ms (*SD*=47). For non-switch trials, this average was 439ms (*SD*=48), and 472 for switch trials (*SD*=59). The difference between the two trial types is significant (*p*=.001, *t*(14)=4.146) and the average switch cost was 34ms (*SD*=37).

Stop-Signal task. Data from the SST shows that participants were also highly accurate on this task. Accuracy on the Go trials was at ceiling (*M*=.97, *SD*=.04), although performance on the Stop trials was more variable (*M*=.7, *SD*=.22). The proportion of incorrect Go responses (measured as 1-Stop trial accuracy) ranged from 3 to 90%[2]. RT data for this task was generally slower than for the GNG task, with an average Go RT across all trials of 567ms (*SD*=56). For non-switch trials, the average Go RT was 549ms (*SD*=69), while for switch trials the average RT was 589 (*SD*=75). The difference between the two trial types is significant (*p*=.008, *t*(14)=3.115), with an average switch cost of 40ms (*SD*=53).

Post-experiment questionnaire (PEQ). Results from the PEQ are summarized in Figure 3. Participants in the low proficiency group scored significantly lower (*M*=44, *SD*=4.9) than those in the high proficiency group (*M*=47.47, *SD*=1.5; *p*=.013, *t*(32)=2.631). Although there is a significant difference between the two groups, the average percentage correct of the low proficiency participants was quite high (44/50=88%), which is to be expected because the stimuli were chosen from the Spanish 2 textbook, which is the lowest-level class that participants were recruited from.

[2] These values are affected by an outlier whose Stop trial accuracy was particularly low: only 10%.

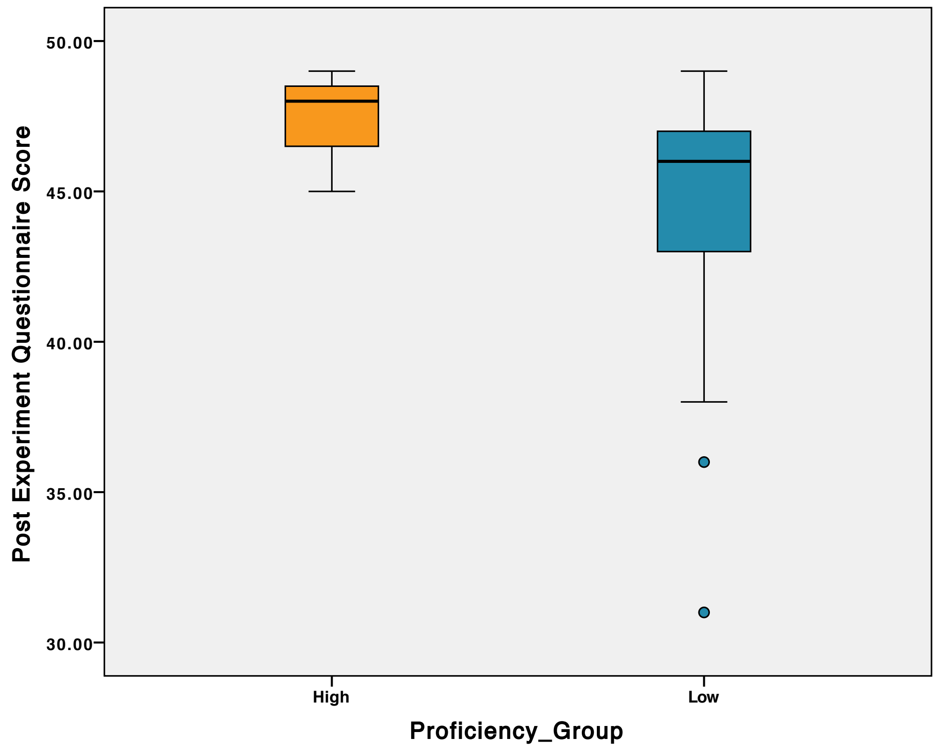

Figure 3. Performance of the High and Low proficiency groups on the Post Experiment Questionnaire.

fMRI.

Semantic decision task.

Univariate analyses. Although the participants were recruited as two groups to ensure sufficient variation in proficiency, the GLM analyses were conducted across all 33 participants to increase power. Rather than dividing the participants into groups, Verbal Fluency (VF) and averaged Self-Rated Proficiency (SRP) scores were used as covariates in a multiple regression analysis to investigate effects of proficiency (see Table 4 for a summary). The multiple regressions were carried out on the Homograph>Spanish (H>S) and Spanish>English (S>E) contrasts. Verbal Fluency and Self-Rated Proficiency did not predict activation for any of these contrasts after FWE-correction, either at the whole brain or ROI level. Before correction (p<.001, k=5), for the H>S contrast I observed a negative relationship between SRP and activity in the right middle, inferior, and calcarine gyri of the occipital lobe. For the S>E contrast, I observed a negative relationship between VF scores and activity in the caudate, as well as a positive relationship between VF scores and activity in the left hippocampus and right temporal pole. When I used SRP as a regressor, I observed a positive relationship between proficiency and activity in the left cerebellum and right STG.

Table 4. *Results from the Univariate Analysis of the SDT*

Contrast	X	y	z	Cluster size (k)	Region Name
H>S_SRP+	n/a				
H>S_SRP-	21	-76	14	9	Right occipital calcarine gyrus
	27	-76	23	6	Right middle occipital gyrus (MOG)
	36	-76	-7	5	Right inferior occipital gyrus (IOG)
H>S_VF+	n/a				
H>S_VF-	n/a				
H>S_AY+	-60	-61	14	14	Left MTG and STG
	42	-79	-7	9	Right MOG and IOG
H>S_AY-	-30	-37	14	5	Left insula
	33	-34	-1	5	Right hippocampus
H>S_BX+	n/a				

H>S_BX-	n/a				
S>E_SRP+	-27	-76	-34	15	Left posterior cerebellum (Crus1)
	60	-31	2	11	Right MTG and STG
S>E_SRP-	n/a				
S>E_VF+	54	11	-7	7	Right superior temporal pole
	-27	-37	8	6	Left hippocampus
S>E_VF-	-6	8	5	8	Left caudate
S>E_AY+	-33	-43	11	5	Sub-gyral left temporal lobe
S>E_AY-	-18	-67	-34	7	Left cerebellum: Crus1 and lobe VI
	45	-79	-4	6	Right MOG and IOG
S>E_BX+	-51	38	-7	8	Left IFG pars orbitalis
S>E_BX-	n/a				

Note. All results are significant at an uncorrected threshold of p<.001 with a minimum cluster size of 5 voxels. Results that did not meet this threshold are listed as n/a. No results survive FWE or FDR correction.

In addition to information about the participants' proficiency, I also investigated how data from the AX-CPT might predict BOLD activity to the SDT. I used reaction times on the AY and BX trials to assess reactive and proactive control, respectively. Unfortunately, none of the results of this multiple regression survived FWE-correction. When examining the uncorrected results (p<.001, k=5) I found that for the H>S contrast, there was a positive relationship between activity in the left MTG and STG, as well as the right inferior occipital gyrus (IOG), and AY RT. I additionally found a negative relationship between AY RT and activity in the left insula and right hippocampus. Finally, for the S>E contrast, AY RT was positively related to sub-gyral activity in the left temporal lobe, and negatively related to activity in the left cerebellum (Crus1 and Lobe VI), as well as the right IOG and middle occipital gyrus (MOG). RT to BX trials showed a positive relationship to activity in the left IFG and MFG for the S>E contrast, but not for the H>S contrast.

Decoding Analysis. Due to the enhanced sensitivity of new multivariate analysis techniques, I also conducted a decoding analysis using the Decoding Toolbox (TDT; Hebart, Görgen & Haynes, 2014) to compare the performance of the two groups. Multivariate pattern analysis refer to methods of analysis that incorporate multiple dependent variables simultaneously, and multivariate decoding specifically describes the mapping of multiple dependent variables to one or more independent variables (the reverse process is referred to as multivariate encoding, see Hebart et al., 2014). These methods of analysis allow for greater sensitivity in relating cognitive variables to patterns of brain activity due to their ability to exploit the covariance across multiple voxels. Furthermore, multivariate analyses provide complementary data to more typical univariate analyses in that they identify regions where activity patterns are more similar within one group than another, as opposed to more or less active. This pattern-based perspective can speak to the CH's claim that L2 learners' brain activity patterns come to converge with that of the L1.

To run TDT requires slightly different preprocessing than for univariate analyses. For these analyses I realigned and co-registered the data, then estimated the effect of Word Type using a standard GLM 1^{st} level analysis in SPM12. The outputs of this analysis were fed into TDT, along with instructions to conduct a searchlight (sized at 4 voxels) analysis using a support vector machine model for classification. The TDT analysis was cross-validated using a leave-one-run out scheme. Outputs of the TDT analysis were then normalized and submitted to independent samples t-tests in SPM12, one comparing High>Low proficiency, and the other Low>High. The High>Low contrast of the TDT analysis identified activity in left caudate (cluster-level *p*=.035, FWE-corrected, k=24) as best discriminating between the two groups, with the anterior and mid cingulate, as well as the left IFG pars triangularis also trending towards significance (cluster-level *p*=.070, FWE-corrected, k=21). This analysis differs from a typical univariate analysis of the High>Low contrast in that it is picking up on the patterns of activity across voxels that best discriminate between the groups, rather than differences in gross activation level. The results of the Low>High contrast did not survive correction, suggesting greater variability in their brain activity. Permutation tests conducted using SnPM (Nichols, 2014) on these data did not reproduce the cluster-level effects observed in the High>Low contrast.

Connectivity analyses. For the GIMME analysis, the groups were divided in order to investigate effects of proficiency on their directed connectivity. In both groups, each ROI's lagged activity was predictive of its current activity. Moving into more detail for the high proficiency group (see Figure 4), pars opercularis of the IFG (IFG_oper) exhibited high connectivity, influencing both pars triangularis (IFG_tri) and the temporo-parietal junction (TPJ) with contemporaneous and lagged connections. In addition, IFG_oper received a lagged connection from the caudate nucleus (CN) and contemporaneous connections from the putamen (Pu) and SMA. In contrast with IFG_oper, the other IFG ROIs were less densely connected. IFG_tri's only connection came from IFG_oper, and IFG_orb's only connection was to influence the CN. Myonly other frontal ROI, the SMA, in addition to its contemporaneous relationship with IFG_oper, also contemporaneously influenced the CN. Regarding the subcortical regions, CN and Pu, their only connections beyond the frontal ROIs were with each other—the CN had both lagged and contemporaneous influence over the Pu.

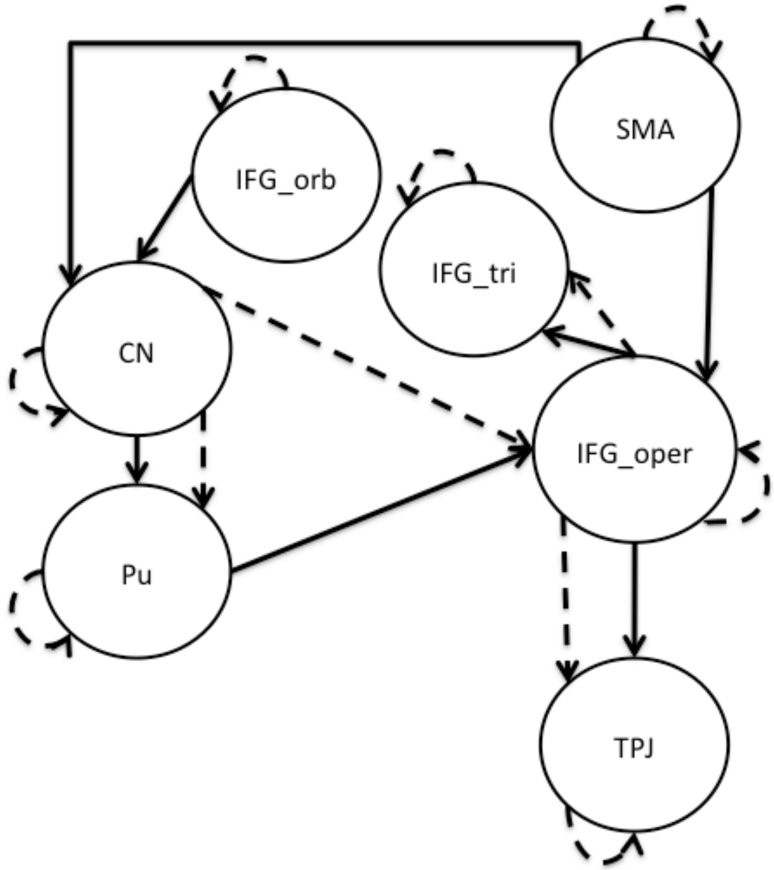

Figure 4. GIMME output for high proficiency learners on the SDT. Dashed lines indicate lagged influence, while solid lines indicate contemporaneous.

For the low proficiency group (see Figure 5), the most obvious difference from the high proficiency group is the increased connectivity of IFG_orb, which rather than influencing the CN with a contemporaneous connection, influences the Pu with both lagged and contemporaneous connections. In addition, rather than simply receiving connections from the CN, the Pu both influences and receives contemporaneous connections with the CN in the low proficiency learners. A further difference is that the connection between IFG_oper and Pu has shifted direction in the low proficiency group so that IFG_oper influences Pu. CN, meanwhile, loses its regulatory role over IFG_oper, instead influencing SMA. In addition, where SMA influenced IFG_oper in the high proficiency group, the direction of that connection has reversed in the low proficiency group. The IFG_tri and IFG_oper connections are also reversed in the low proficiency group, such that IFG_tri is influencing IFG_oper. The one connection that remains the same in both groups is between the IFG_oper and TPJ.

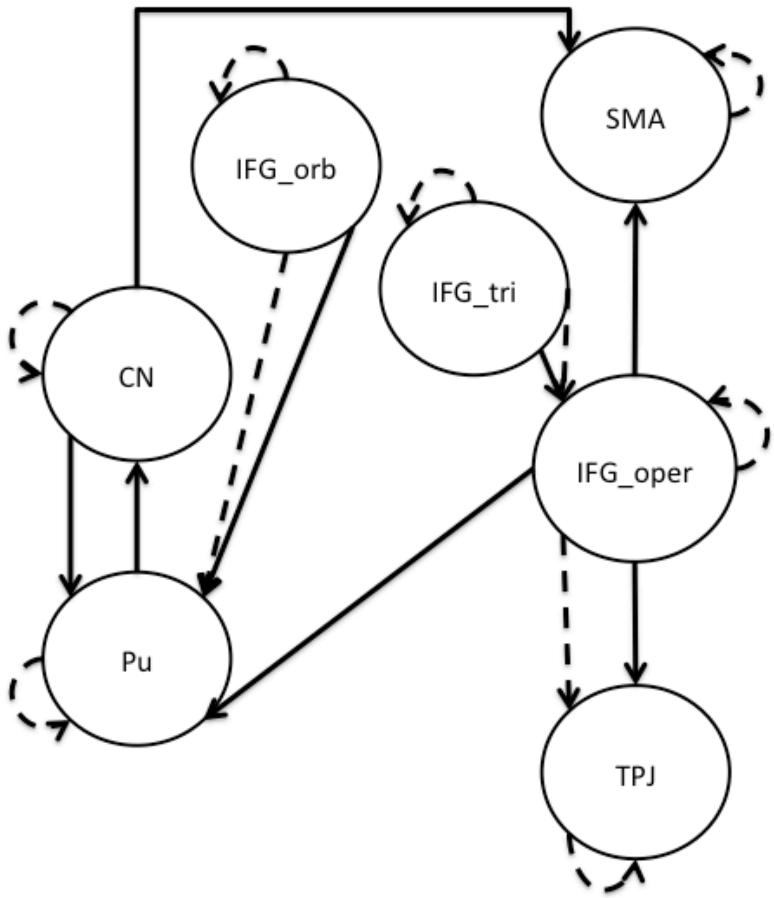

Figure 5. GIMME output for low proficiency learners on the SDT. Dashed lines indicate lagged influence, while solid lines indicate contemporaneous.

Control Tasks. I also conducted whole-brain multiple regression analyses on the contrasts of interest, Nogo>Go and Stop>Go, with VF, SRP, and AX-CPT performance as covariates. For the NoGo>Go contrasts, I observed activity in the right precentral gyrus, left lingual and calcarine gyri of the occipital lobe, and left MOG, although it did not survive FWE-correction ($p<.001$, k=5). Neither VF nor SRP significantly predicted activity after FWE-correction. In addition to the multiple regressions, I conducted comparisons of the two groups for the Nogo>Go contrast. Low proficiency learners showed more activity in the left precentral gyrus, IFG, STG, and MTG, although these effects do not survive FWE correction ($p<.001$, k=5). High proficiency learners showed more activity in the right hippocampus and posterior cingulate, as well as the left caudate and ACC, ($p<.001$, k=5) although these results also do not survive FWE correction. Analyses of the relationship between the AX-CPT and GNG data show that greater activity in the right superior temporal pole was significantly predicted at peak voxel level by worse performance on the BX trials of the AX-CPT ($p<.05$, FWE-corrected) and additionally at the cluster level in the left superior temporal pole (cluster-level $p<.05$, FWE-corrected, k=56). In contrast, better performance on the BX trials significantly predicted greater activity at peak voxel level in the left orbital IFG ($p=.059$, FWE-corrected) and at the cluster level in right IFG pars triangularis ($p<.05$, FWE-corrected, k=59) and in medial SFG ($p<.05$, FWE-corrected, k=49).

Planned conjunction analyses to examine if shared regions supported bottom-up control and second language processing were conducted between the S>E and Nogo>Go contrasts and the H>E and Nogo>Go contrasts for the low>high comparison. These did not yield significant results. The same analysis was also run for the high>low comparison. Again, the H>E and Stop>Go contrasts did not overlap, but there was overlap between the S>E and Nogo>Go contrasts in the left hippocampus, although this result does not survive FWE-correction.

For the SST, the Stop>Go contrast found activity in the right superior frontal and precentral gyri, left precentral gyrus extending into the middle and superior frontal gyri, left lingual gyrus extending into the fusiform and IOG, right lingual gyrus extending into the IOG, left calcarine gyrus, left cerebellum (IV,V,VI), and right insula, inferior frontal operulum and rolandic operculum, although none of this activity survived FWE-correction. Comparisons of the

Stop>Go contrast between the two groups showed that for high proficiency learners, the bilateral lingual gyri were more active, extending into the right fusiform and cerebellum (lobes IV and V), as well as the left cerebellum (IV,V and vermis3), hippocampus, and precuneus (cluster-level $p<.05$, FWE-corrected, k=112). In addition, high proficiency learners activated the bilateral calcarine gyri extending bilaterally into the precuneus and lingual gyri, as well as the vermis of the cerebellum (lobes IV and V) (cluster-level $p<.05$, FWE-corrected, k=104). For the low proficiency learners, no areas were significantly more active than for the high proficiency learners. AX-CPT performance did not significantly predict activity for the SST.

Planned conjunction analyses to examine if shared regions supported top-down control and second language processing were conducted between the S>E and Stop>Go and the H>E and Stop>Go contrasts for the low>high comparison. These did not yield significant results. The conjunction of the Stop>Go and S>E contrasts in the High>Low comparison overlapped in the right lingual gyrus, although this result did not survive FWE-correction. In addition, ROI analyses of the Nogo>Go and Stop>Go contrasts did not reveal significant activity after correction in any of the predicted regions.

Discussion

The current study aimed to examine the influence of L2 proficiency and mapping consistency (as manipulated by the use of language ambiguous and unambiguous stimuli) on the use of control by L2 learners. I expected that if bottom-up control increases with proficiency, I would see more activation in the parietal-putamen motor loop, rather than the IFG-CN executive control loop, for higher proficiency learners. I also recognized that the IFG may be involved in bottom-up control (Lenartowicz et al., 2011) and consequently, I expected that if I observed greater/equivalent IFG activity for highly proficient learners, I would find it in pars triangularis.

Furthermore, I identified the three subcomponents of the IFG (pars opercularis, pars triangularis, and pars orbitalis) as regions of interest in order to test a current theory of cognitive control that suggests that the IFG is organized according to a rostral-caudal gradient (Uddén & Bahlmann, 2012) such that abstract control is exerted more rostrally (i.e., in pars orbitalis) while less abstract control relies on more caudal sections.

The results of my behavioral data analysis confirm that the two groups of participants differ significantly in their self-rated (as assessed by the LHQ) and objective L2 proficiency (as assessed by the L2 Verbal Fluency task, SDT, and PEQ). Furthermore, participants in both groups performed near ceiling on the GNG and SST, although there was a significant group difference on the AX-CPT, which I will return to in Chapter 4's General Discussion. The remainder of the discussion for this experiment will focus on the MRI results.

Semantic Decision Task.

Effects of Proficiency. Despite significant behavioral differences between the two groups, univariate analyses of the fMRI data failed to find significant differences in activity between the two groups that survived correction for multiple comparisons. This is likely due to power issues with the design addressed above. If we consider the uncorrected data, we see a pattern that is generally congruent with my predictions. For unambiguous Spanish words, higher proficiency (as measured by Verbal Fluency) is associated with less activity in the caudate, a top-down control region, as well more activity in the left hippocampus and right temporal pole. Activity in these regions, which are typically associated with memory (Cohen & Squire, 1980) and semantics (Pascual et al., 2015), likely reflects the superior ability of the high proficiency learners to perform the task, which required participants to not only access the meaning of the word, but also assess the size of that representation. In addition, greater proficiency as measured by self-ratings was associated with more activity in the left cerebellum and right STG. The cerebellum is commonly implicated in motor control (Mariën et al., 2014) and the particular region that I observed, the Crus1, is typically involved in more language-specific articulatory control. Consequently, activity in this region may reflect the use of bottom-up control by the higher proficiency learners. This proposition is further supported by its co-occurrence with activity in the right STG, as rSTG has been implicated in language control in more balanced bilinguals (see Luk, Green, Abutalebi & Grady, 2012). Furthermore, Manuel et al. (2010) observed significant decreases in activity in right temporo-parietal cortex after training on the Go/No-go task, suggesting that rSTG reflects bottom-up attentional control processes.

In contrast, for homograph words, I found that lower self-rated proficiency was associated with greater activity in the right middle, inferior, and calcarine gyri of the occipital lobe. In the left hemisphere, these areas are considered part of the ventral meaning network and are connected via the IFOF to frontal and temporal semantic processing regions. That the lower proficiency participants showed greater activation in the right homologue of this region during L2 processing likely reflects a compensatory mechanism, as has been observed previously in unbalanced bilinguals (see Hernandez et al., 2001; Hosoda et al., 2013).

In sum, the univariate analysis revealed proficiency-based differences in L2 semantic processing in subcortical and posterior regions, including the caudate and superior temporal lobe, that suggest a shift from top-down to bottom-up control processing during the SDT. I did not observe the differences I expected in the IFG, but as we will see in the following sections, the two learner groups did in fact differentially recruit that region, even if the gross activity level was similar across groups.

Multivariate Decoding Analysis. Results from this analysis suggest that the patterns of activity in the left caudate, anterior cingulate, and left IFG pars triangularis best distinguish between high proficiency and low proficiency learners. These regions are all part of the typical language control network identified by Abutalebi and Green (2008). That I observe significant results in the High>Low direction, rather than Low>High, indicates that there are more shared similarities among the high proficiency learners, making their data easier to classify. This reduced variability in the brain response is corroborated by the reduced variability in the high proficiency learner's behavioral data (see Table **1** and Table **3**, as well as *Figure **3***). These results suggest that even though I only observed gross changes in activity level in the caudate between the two groups, as discussed above, the learners' proficiency was also reflected in the multivariate patterns of activity in the cingulate and IFG elicited by the semantic decision task. Furthermore, the enhanced similarity among the high proficiency learners can be interpreted as supporting the predictions of the Convergence Hypothesis, as it suggests that with increased proficiency L2 learners will rely less on compensatory brain activity outside the core language network (Green, 2003).

Connectivity Analyses. In addition to the multivariate analysis, connectivity analysis also allows for a more nuanced approach to the data than typical univariate analyses. In this experiment, connectivity analyses allowed for the assessment of the Conditional Routing model, a model of bilingual language control (Stocco et al., 2014). According to the Conditional Routing model, bilinguals select languages either through cortico-cortical connections (when selecting an already activated language) or through basal ganglia mediated signal routing (when selecting a less proficient or previously inhibited language). In my connectivity analysis, I observed that communication between the basal ganglia and the inferior frontal gyrus was recruited for both high and low proficiency L2 learners during a semantic decision task. Furthermore, extending the predictions of the Conditional Routing model, I observed that the structure of these communications differed between high and low proficiency learners, suggesting that the basal ganglia routing system becomes more efficient with increased proficiency.

Specifically, in high proficiency learners, I observed an efficient processing system between the basal ganglia and frontal cortex. The orbital IFG affects the CN, which affects the Pu, which influences the activity in IFG pars opercularis, which also activates IFG pars triangularis. This pattern of activity can be interpreted in light of theories proposing a rostro-caudal gradient of abstraction in control and language processing in the IFG (Uddén & Bahlmann, 2012). Specifically, they suggest that IFG_orb is more involved in abstract control, as well as semantic processing. The area that IFG goes on to activate, the CN, is also known for its participation in activities governed by abstract rules. This suggests that participants are likely activating the semantic content of the word, then interpreting that content in the context of the rules of the task. The following activity in the putamen and caudal aspects of the IFG are also consistent with the rostral-caudal gradient model, as both the putamen and caudal IFG are associated with more simple S-R associations. In addition to this long chain of activity between the BG and IFG, I also observed influence from the SMA to the CN, likely an example of motor feedback.

In low proficiency learners, the system appears less efficient. IFG_orb, rather than influencing the CN, influences the Pu, which goes on to both influence and receive influence from the CN. Pu is also influenced by IFG_oper, and presumably the information from both IFG_orb and IFG_oper is communicated to CN, which influences the SMA in conjunction with

IFG_oper. Overall, this network seems to reflect a more motor-centered approach to the task—that is, participants were pressing buttons, but not necessarily taking a systematic approach to their decisions, which is reflected in their significantly lower accuracy for the L2 trials.

To review, the L2 proficiency of the participants was reflected in the BOLD correlates of their semantic processing in several ways. First, there was lower overall activation, as well as greater inter-participant multivariate similarity and network efficiency in the top-down control network for the high proficiency learners. In addition, high proficiency learners showed more recruitment of bottom-up control regions. In contrast, low proficiency learners showed less inter-participant similarity, worse network efficiency, and no overall differences in activation for the unambiguous L2 words compared to the high proficiency learners.

Relationship with Cognitive Control. Given the relationship between language and cognitive control, I also expected participants' individual differences in control to affect their semantic processing. Although the AX-CPT does not measure bottom-up control, as the relationship between cue and probe is not consistent throughout the experiment, it does assess two types of top-down control: reactive and proactive. I found that participants' reactive control (as measured by AY RT) was predictive of their response to language ambiguous words (measured by the H>S contrast). Specifically, I found that participants who had worse reactive control showed more activity in sensory areas, such as the right inferior occipital lobe and left superior temporal lobe, as well as a typical language processing area, the left middle temporal gyrus. This suggests that those participants with worse reactive control were more focused on the form of the word, possibly in order to determine language membership.

In contrast, those participants with better reactive control (as assessed by AY RT) showed greater activity in the left insula and right hippocampus. Given the role of the hippocampus in relational memory binding, this suggests that those participants were able to draw on pre-existing connections between the word and its form. The additional insula activation may have been caused by sub-vocal articulation of the words (Price, 2010) but is more likely related to the role of the insula in top-down inhibition. Boehler et al., (2010) have found that individual differences in stopping efficiency during the stop-signal task are associated with the level of activity in the insula. The activity of this region during the semantic decision task for language ambiguous words confirms my prediction that mapping consistency is related to the degree of top-down control required during second language learning.

In addition to predicting activity for language ambiguous words, performance on the AX-CPT was also predictive of activity for unambiguous second language words (as measured by the S>E contrast). When I examined a measure of reactive control (AY RT), I found that better reactive control was related to activity in the regions of the cerebellum commonly associated with language processing (VI and Crus1) and specifically verbal working memory, although on the contralateral side. This suggests that those participants with better reactive control were able to supplement their performance via bilateral activity in the cerebellum. In addition, those participants with better reactive control also showed greater activity regions associated with successful, rather than failed, inhibition (the right middle occipital gyrus; Ramautar et al., 2006). That we observe activity in this region during the semantic decision task suggests that those participants with better reactive control were better able to inhibit the first language in order to process the meaning of the second language words.

In contrast to the reactive control measure, which significantly predicted activity for both language ambiguous and unambiguous words, the proactive control measure only significantly predicted activity for the language unambiguous words. Specifically, I found that participants with worse proactive control relied more on activity in the frontal control network, specifically the left inferior and middle frontal gyri. The overall differences between these two patterns of results suggest that the reactive control measure was more sensitive to activity in sensorimotor control regions, while the proactive control measure was predictive of activity in the frontal control network. Both of these processes are critical to language selection, and these results show that using the AX-CPT as a regressor allows one to isolate the regions involved in each of these aspects of language use.

Control Tasks. In addition to analyses using the AX-CPT as a regressor, I also collected BOLD data while participants completed the GNG and SST in order to assess the similarity between the non-linguistic control elicited by these tasks and the language control required during the SDT. Analyses of the control tasks indicate that the GNG and SST tasks were successful in eliciting bottom-up and top-down control, respectively. Regression analyses with proficiency and AX-CPT performance found that the GNG task was significantly predicted by proactive control performance (as measured by the BX trials) such that improved performance was associated with greater activity in the IFG, replicating Lenartowicz et al (2011). In addition, worse performance was associated with greater activity in the parahippocampal gyri, which likely reflects the critical memory component in both proactive control and the No-go trials of the task, which were ¼ as frequent as the Go trials.

In contrast, activity during the SST was better predicted by language background than by AX-CPT performance. This is somewhat surprising, as one would expect the SST to also be predicted by AY performance, but the measurement validity between cognitive control tasks is known to be poor (Miyake et al., 2000) and there is not a 1:1 relationship between top-down/bottom-up control and reactive/proactive control. Nevertheless, the fact that language proficiency predicted activity suggests not only that the task was indeed measuring top-down control, but moreover the location of that activity (in the bilateral fusiform and lingual gyri) suggests that their practice in language control may be affecting their non-linguistic control systems, as has previously been observed by Rodriguez-Pujadas et al. (2013).

My primary analysis of interest for the control tasks, however, was their conjunction with the SDT in high and low learners. What I saw from that analysis was that in high proficient learners the S>E and Nogo>Go contrasts overlapped in activity in the left hippocampus, while the S>E and Stop>Go contrasts overlapped in the right lingual gyrus.

The former overlap likely results from the increased memory demands in the two conditions. The No-go trials only occurred 20% of the time, and consequently required not only an inhibition of the pre-potent Go response but also recall of the appropriate response. Similarly, the Spanish trials likely required more effortful recall of the associated meaning than in English.

The latter overlap, although it did not occur in a region of interest, occurred in a region that has been previously implicated in language switching and decision making (Lei et al., 2014; Ma et al., 2014; Román et al., 2015) These results provide partial support for my hypothesis that linguistic and non-linguistic control are processed similarly, although I would have expected to observe overlap with the Stop-Signal task in the low proficiency learners or for a homograph contrast. It may be that the greater BOLD response diversity in the low proficiency learners (as assessed by the multivariate decoding analysis) made it less likely to observe a common overlap between the language and control tasks for that group.

In sum, the analysis of the control tasks revealed some similarities between language and cognitive control. One such is the importance of memory, as the identification of the parahippocampal gyri and hippocampus in proactive control and as a shared region between semantic processing and Go/No-go processing demonstrates. Specifically, the activation of the hippocampus during the SDT and GNG tasks likely reflects its role in associative binding, as both tasks require participants to map stimuli onto infrequent responses. Another interesting similarity concerns the role of the lingual gyri, whose activity was both predicted by language proficiency and also shared during semantic and top-down control processing. The shared activation of this region may be related to its role in visual attention (see Meffert et al., 2016); future work could examine this by comparing the language control networks during auditory vs. visual versions of the SDT and SST.

Limitations. Before concluding this chapter, however, it is necessary to discuss a substantial limitation of the results of this experiment. In the SDT, the decision to a) include homographs and b) recruit from beginning learners greatly restricted the total number of possible stimuli, leading to lack of power. Although I made attempts to maximize the power of MRI design—e.g., using a block design, acquiring the images without acceleration—and to maximize the sensitivity of the MRI analysis by using a multivariate decoding approach, these were not sufficient to override the lack of stimuli. Part of the reason for this design flaw is that the fMRI power analysis tool (specifically, fMRIpower; Mumford & Nichols, 2008) available at the time I was designing and piloting the study required an estimate of effect size. Because the semantic decision task I chose is not common (although it has been previously used, see Branzi et al., 2016) I was unable to obtain an effect size estimate from the literature to use in a power analysis.

Since finishing data collection, however, Durnez and colleagues have developed a new tool, NeuroPower, that does not require an effect size estimate to operate (see neuropowertools.org; Durnez et al., under review). Post-hoc power analyses using NeuroPower suggest that with my current sample size, the uncorrected power of my study is approximately 60% (see Figure 6).

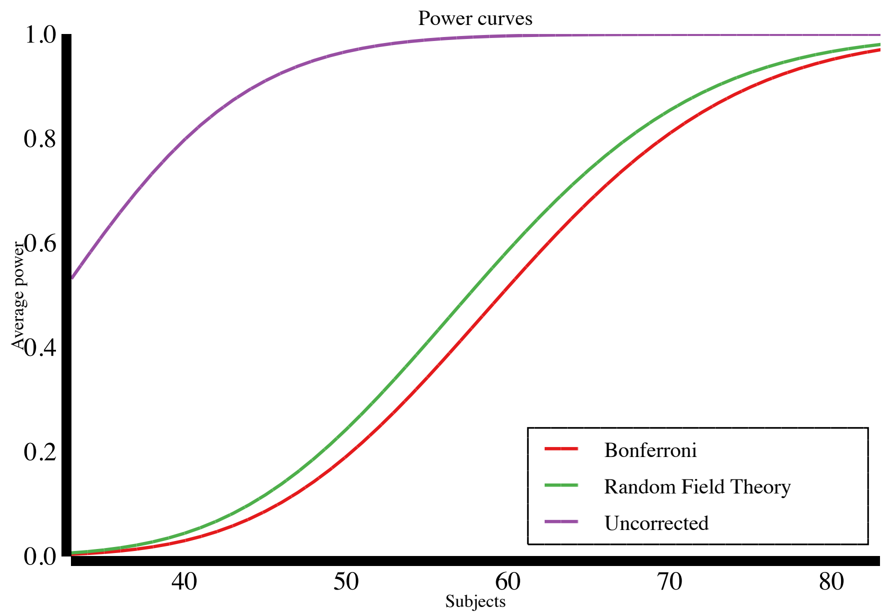

Figure 6. NeuroPower analysis of the univariate fMRI data

While post-hoc analyses are problematic (see Mumford, 2012) and the NeuroPower tool is meant to be used prospectively with pilot data, it is worth noting that after correction, however, the power estimate for my study falls to approximately zero. Although this is unfortunate, the presence of the NeuroPower toolbox at a minimum guarantees that I will not have such problems in the future. Bearing these limitations in mind, the following sections will interpret the results I did observe in the light of current theories of cognitive and language control.

Conclusions

The goal of this experiment was to examine how language learners of varying proficiency use cognitive control during semantic processing. The analysis of the behavioral data and the multi-modal approach to the neuroimaging data revealed that low and high proficiency learners draw on different regions associated with top-down and bottom-up control, respectively, during L2 semantic processing. Furthermore, learners' proficiency was also evident in their multivariate patterns of activity, which were more similar among high proficiency learners, and their connectivity between cognitive control regions, which were more efficient in high proficiency learners.

Critical information towards this goal was also gained through the analysis of the cognitive control tasks, the GNG and SST. Conjunction analyses of the cognitive control tasks and the SDT found overlap between linguistic and non-linguistic control, particularly in regions associated with memory and visual attention. In addition, language proficiency was predictive of activity during the SST but not the GNG task, which suggests that the top-down control mechanisms are at least partially shared. How these data inform current theories of cognitive and language control will be further addressed in the general discussion presented in Chapter 4.

Chapter 3: Cognitive Control Training and L2 Performance

As reviewed in Chapter 1, the current literature on cognitive control suggests that it is sensitive to training, at both a behavioral and structural level (e.g., Berkman et al., 2014; Takeuchi et al., 2010). Combining this information with what we know about the significant overlap between the areas involved in cognitive control and L2 processing, it follows that training in one of these domains should affect processing in the other. This hypothesis is supported by work from Sullivan et al. (2014) and Novick et al. (2014), who found that second language training affected brain responses to the Go/No-Go task, and that training on the n-back task improved participants' ability to recover from garden-path sentences, respectively.

More directly applicable to this experiment are the results of a recent study by Liu, Dunlap, Liang and Chen (in press). Liu et al. examined how inhibition training using the Simon task would affect participants' language switching ability between their first language (L1) and a recently trained language (Lnew). Participants' inhibitory control abilities were initially assessed via the Simon task and the participants were split into two groups: high and low. Both groups received training on the Lnew (Korean) before performing a language-switching pre-test. The pre-test showed significant differences between the high and low groups, such that the low group showed asymmetric switching costs while the high group did not. After this test the low inhibitory control group received training on the Simon task as well as training on additional Lnew words, while the high group received language but not inhibitory control training. These learning sessions were followed by a language switching post-test, where the authors found that both the high and low inhibitory control groups showed symmetric switching costs in the language-switching task.

In addition to their behavioral results, Liu et al. (in press) also recorded EEG data while the participants completed the language switching tasks. Their ERP analysis focused on two time-windows, the N2 and the LPC. They observed that the high and low inhibitory control groups differed in the amplitude of the LPC before training, such that the high group showed larger LPCs to switch trials in Lnew than L1, while the low group showed LPCs of similar amplitude to both languages. After training, however, the low group's LPC pattern became more similar to the high group.

Most relevant to this experiment, however is that Liu et al. (in press) trained top-down control via the Simon task. In their implementation, the Simon task consisted of a cue (either a red or blue block) followed by an arrow, and then a series of **** to indicate that participants should respond. The cue indicated to the participants if they should press the button corresponding to the same direction as the arrow or the opposite direction (i.e., whether they should make a congruent or incongruent response). During the training sessions the association between the color and the type of response was switched between blocks, making it an inconsistent cue that would require top-down control, rather than allowing for bottom-up control. Consequently, Liu et al.'s finding that training on the Simon task affected participants' performance on the language-switching task is in line with my predictions as outlined in the Current Study section (p. 23) and detailed below.

As mentioned in the Current Study section, Experiment 2 examines the relationship between cognitive control and L2 lexical processing by comparing the effects of bottom-up, top-down, and sham control training on L2 lexical processing. Like in Experiment 1, SST training tests top-down control and GNG training tests bottom-up control. The sham training uses a two alternative forced-choice task. My predictions for this study were that the SST training will be more effective than GNG or sham training.

While that predictions may seem to run counter to the results of Experiment 1, which associate bottom-up control with higher proficiency, the reasoning is based on the fundamental difference between bottom-up and top-down control, which is that bottom-up control is stimulus driven and top-down control is generated internally. While in Experiment 1 I examined how each type of control is used within a domain, in Experiment 2 I examine how training on each type of control may transfer across domains. Because bottom-up control is stimulus driven, training on the GNG, a *non-linguistic* bottom-up task, should not affect the application of bottom-up control to language stimuli. That is, it shouldn't transfer. In contrast, the SST trains top-down control, which should theoretically be less modality specific and consequently should transfer.

Investigating these types of training provides critical behavioral evidence to complement the fMRI analyses of Experiment 1, as it is relatively common for neuroimaging and behavioral studies to be sensitive to different types of effects (e.g., Chen, Shu, Liu, Zhao & Li, 2007; Sullivan et al., 2014). Specifically, Experiment 2 further addresses the question from Experiment 1 (i.e., does proficiency modulates the type of control used by L2 learners) through the potential for an interaction between Training Type and Proficiency. Specifically, if Low proficiency learners rely on top-down control more than High proficiency learners, as I observed in Experiment 1, then Low proficiency learners should show greater effects of SST training than High proficiency learners.

Methods

Participants. Participants in this study were 135 native English speakers recruited from the Psychology department subject pool and compensated with course credit. The final sample consisted of 106 participants (84 female), and participants' ages ranged from 18 to 24, with an average age of 18.88 (*SD*=1.21)[3]. Five participants were excluded because they had prior knowledge of Chinese, 13 participants were excluded for failing to reach the learning threshold on the language training task, and another 11 participants were excluded due to equipment failure.

Materials. Several of the tasks in this study, including the LHQ, AX-CPT, the SST task and the GNG task are the same tasks as in Experiment 1. The language training, sham control training, and animacy judgment task are unique to this experiment and are described in further detail below.

Language Training. Participants in this study were trained to varying levels of proficiency on 60 words from an unknown language, Mandarin Chinese (for a full list see Appendix B: Chinese Stimuli from Experiment 2). Of these 60 words, 20 were Chinese-English homophones. The homophones were initially selected from an introductory Chinese textbook by a Chinese-English bilingual and then refined down to 20 by a native English speaker. All stimuli were recorded by a native Chinese speaker and overall amplitude was adjusted after recording to 70dB.

Vocabulary training began with a brief exposure phase, where participants heard each word twice while viewing its associated picture. Pictures were black and white line drawings taken from the Boston Naming Test (Kaplan, Goodglass & Weintraub, 1983). Participants determined the presentation rate of the words during this phase by pressing the Spacebar to initiate the next word. After initial exposure, participants began active training.

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[3] The average age and gender information is for a subset of 102 participants, as a bug in the LHQ caused it to discard the results of four participants.

During the active training phase participants heard a word and had to choose which of four pictures matched the meaning of the word (see Figure 7). A fixation cross was presented between each word trial, and participants clicked on the fixation cross to begin the next trial. Participants were given feedback on their responses (a green box around their selection for correct responses, a red box for incorrect) and were either trained to low proficiency (50% or greater), or high proficiency (80% correct or greater; this threshold was originally 90%, but after multiple participants failed to reach the threshold, it was changed to 80%). Presentation of the stimuli was blocked such that proficiency was assessed every 15 trials, ensuring that all participants received a minimum of one training block.

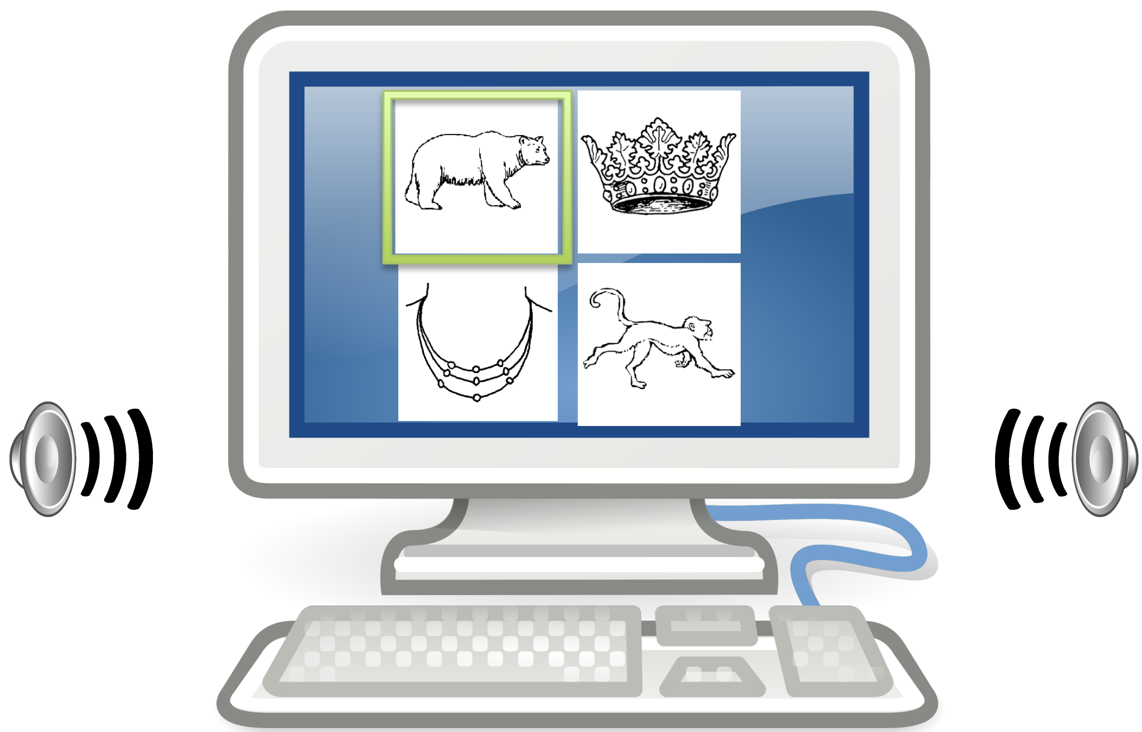

Figure 7. Language Training during Experiment 2. Participants indicated their response by clicking on their chosen picture.

Sham Control Training. All participants were assigned to one of three control training conditions: GNG, SST, or sham. All training conditions lasted for 30 minutes. All participants were instructed that “When 0000 appears in green, press the left button as quickly as possible” followed by instructions regarding the red zeros. All instructions ended with the sentence "Both speed and accuracy are equally important". In the GNG and SST conditions participants instructed that "If 0000 appears in red, do not make a key press", and in the SST condition participants received the additional instruction that "If 0000 appears in green and changes to red, do not make a key press". The sham training task was a two alternative forced-choice task, and consequently in the sham training, participants were instructed to press the opposite key (1 or 5 on the button box) when 0000 appeared in red. Participants responded to the two stimulus types using the index finger on each hand.

Animacy Judgment. The final assessment of the participants' knowledge of the Chinese vocabulary was assessed with an animacy judgment task. In the animacy judgment task, participants heard a previously learned word and pressed either the F or J key to indicate if the word represented an animate or inanimate object (assignment of the key to the response was counterbalanced across participants, and indicated via a sticker on the key).

Procedure. Participants filled out the LHQ, and then began language training. Participants were exposed to all the words twice, and then trained using the four-choice test. When they achieved 50% accuracy, participants in the low proficiency group moved on to the control training phase, and they were then trained on the SST, GNG, or sham control training task. Control training lasted for exactly 30 minutes, as that was the median duration of a set of 20 training studies reviewed by Spierer et al. (2013). The same procedure was followed for the high proficiency participants, except that they were trained on the vocabulary until they reached 80% accuracy.

Once all participants completed their vocabulary and control training, they completed an animacy judgment task on the new words. After animacy judgment, participants also completed the AX-CPT. AX-CPT data was collected for 108 of the 135 participants; the 27 participants who did not complete the task ran out of time.

Results

Analyses for this study were carried out via a 3 (Control Training Type) x 2 (Word Type) x 2 (Proficiency) mixed ANOVA, with accuracy and reaction time (RT) on the animacy judgment task as the dependent variables. Overall, I expected a main effect of proficiency on the animacy judgment task, such that participants in the high proficiency condition should perform faster and more accurately than those in the low proficiency condition. I expected that this effect of proficiency would be moderated by Word Type, such that both low and high proficient learners should perform worse on homophones than unambiguous L2 words. In addition, as mentioned in the introduction to this chapter, I expected that there would be an effect of Control Training Type, such that learners who complete the SST training would perform significantly better on the animacy judgment task than learners in the GNG or sham training groups. I further expected that these two effects should interact, such that the advantage of SST training would be stronger for the low proficiency group. I also predicted a three-way interaction between these factors, such that the type of control training participants receive may influence the effects of proficiency and word type. Specifically, one might expect that SST training would be most advantageous to low proficiency learners processing homophones, while the effect of GNG or sham training should be invariant across proficiency levels and word types.

The results of my analysis confirmed some but not all of these predictions. First, there was not a significant main effect of Word Type, either on Accuracy or RT (all $Fs<1$, $ps>0.1$). Subsequent analyses conducted without this factor and with accuracy on the AY and BX trials of the AX-CPT included as covariates[4] find that for Accuracy, there are no significant main effects of Control Training Type or Proficiency (see Figure 8) or interaction between these two factors.

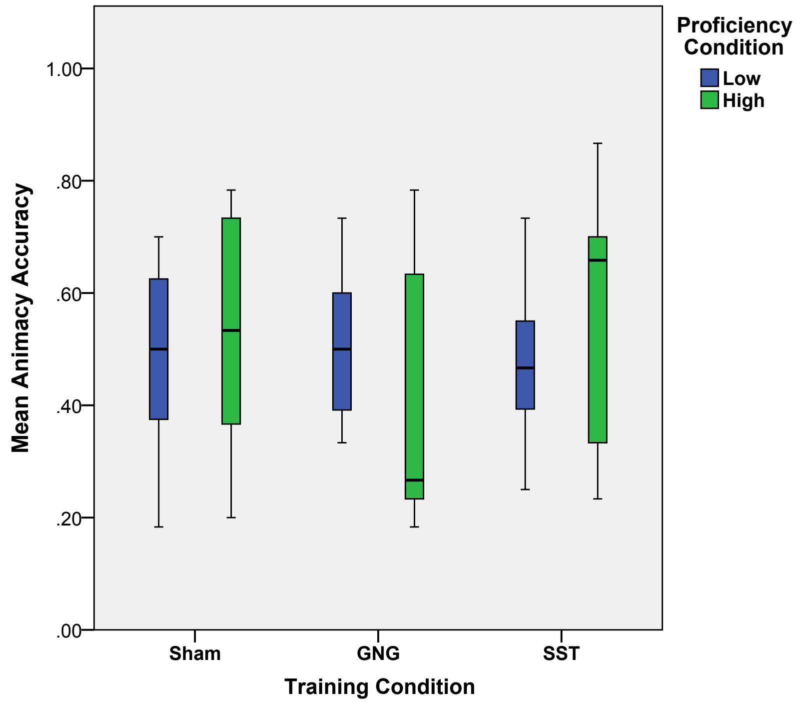

Figure 8. Accuracy Performance on the Animacy Judgment Task.

Analyses of the RT data proved to be more sensitive to the manipulations (see Figure 9). In the 3 (GNG, SST, Sham) x2 (High, Low) ANOVA with AY and BX RT entered as covariates, there was a significant main effect of Control Training Type ($F(2, 105)=3.313$, $p=.041$) and a significant interaction between Control Training Type and Proficiency ($F(2, 105)=4.951$, $p<.01$). Follow-up ANOVAs revealed that there was a significant effect of Control Training Type in the

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[4] Performance on the AX-CPT was not included as a covariate in the original 3x2x2 ANOVA because it was a mixed ANOVA. Subsequent analyses included the relevant AX-CPT data for the AY and BX trials in order to control for pre-existing individual differences in control across groups and better isolate the effect of Control Training Type.

Low Proficiency group ($F(2, 58)=4.048$, $p=.023$), which was marginal in the High Proficiency group ($F(2, 47)=2.685$, $p=.080$).

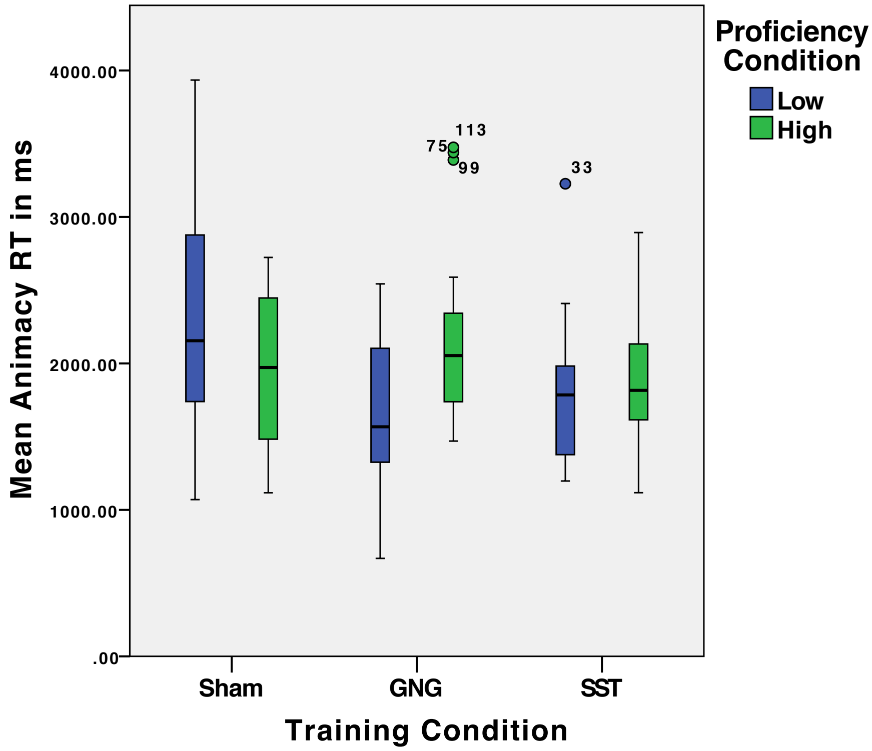

Figure 9. Reaction Time (in ms) on the Animacy Judgment Task.

Post-hoc tests of RT performance in the Low proficiency group using Bonferroni corrections found that SST training significantly speeded performance on the animacy judgment task in comparison to participants who underwent the Sham training. In comparison, participants in the High proficiency group did not show significant differences between the different control training conditions.

Discussion

The results of this experiment provide limited support for my predictions. Although I did observe the expected interaction between Proficiency and Control Training condition such that top-down control training improved performance on the animacy judgment task particularly for Low proficiency learners, this pattern was observed in the RT data only. In the following sections I offer potential explanations for why this effect was not present in the accuracy data, expand on the possible interpretations of the RT data, and offer suggestions for future research.

Accuracy Data. The null effect in the Accuracy data is likely due to the lack of overall variation in participant responses for that task. Average accuracy on the Animacy task was at 49.3%, which is essentially chance (50% for a two-choice task). Responses ranged from 18% to 87% correct, but the standard deviation of approximately 18% shows that most responses fell between 31% and 67% correct. The poor performance on this task may be due to a number of factors, including the number of stimuli to be learned (60) and the nature of the Animacy test (recall-based).

The number of stimuli to be learned was based on previous data from the Brain, Language, and Computation lab, which found that participants learning a set of 90 Mandarin vocabulary words using the 4-choice testing paradigm advanced relatively quickly, with an average of 63% accuracy after one 15-minute training session and an average of 81% accuracy after the second (for more details, see Lan, Fang, Legault & Li, 2015). Given this, I wanted to ensure sufficient difficulty by including a large set of stimuli.

The critical difference between the Lan et al. study and this one, however, is that Lan et al. used the 4-choice testing paradigm as an outcome measure, while I used it as a means of training. My outcome measure, the Animacy judgment test, was based on participants' recall of the words, rather than the recognition ability tested by the 4-choice paradigm. Recall is known to be more difficult than recognition (Gillund & Shriffin, 1984) and in retrospect it is unsurprising that participants in my study, who in some cases received as little as 15 trials of training beyond the exposure session, did not perform significantly above chance on the Animacy test.

Reaction Time Data. Although I did expect to find differences in accuracy performance across my groups, accuracy is not always the most sensitive measure of cognitive performance (e.g., McLaughlin et al., 2004). Consequently, the RT results are worthy of further discussion. To review, I found that SST training significantly speeded performance on the Animacy task for the Low proficiency group compared to GNG and Sham training, which did not differ from each other. Furthermore, although there was a marginal effect of Control Training Type in the High proficiency group, follow-up post hoc tests failed to detect a difference between the three groups. This pattern supports my prediction that top-down control training is particularly beneficial to learners at the beginning stages of learning. It also supports my prediction that Sham and bottom-up control training would not affect L2 performance, regardless of the proficiency of the learner.

One potential complication for this account is that the two learner groups in this study did not differ significantly in their accuracy performance for the Animacy task, which could call into question whether the two groups should be separated at all. However, the two groups were differentially exposed to language training and differ significantly in the number of language training trials they completed ($t(128)=10.091$, $p<.001$). This is critical because the central hypothesis behind the expected interaction between Proficiency and Control Training Type hinges on the development of automated stimulus-response associations, rather than explicit knowledge. Consequently, I believe the observed interaction is meaningful, and suggests that the automatization of stimulus-response associations for foreign language vocabulary may precede the development of explicit vocabulary knowledge.

Future Studies. The results from this study suggest that future work looking to examine the effect of cognitive control training on vocabulary acquisition may benefit from using a dependent measure of vocabulary recognition, rather than recall. In addition, future studies could investigate the hypothesis that the effect of control training precedes vocabulary knowledge through the use of neurophysiological measures such as ERPs, which have been previously shown to be more sensitive than behavioral measures to L2 vocabulary learning (e.g., McLaughlin et al., 2004; Liu et al., in press).

Beyond fine-tuning the design, future studies could build on these results to better understand how language learners use cognitive control and how training on cognitive control could potentially improve L2 learning outcomes. For example, the results from this study suggest that the role of cognitive control during L2 lexical access changes even before learners develop explicit L2 knowledge. Future work could investigate at what point that change occurs (perhaps using the fast-mapping technique employed by Shtyrov, Nikulin & Pulvermuller, 2010), and if it changes throughout the life of the learner based on their language use. For example, many heritage language learners grow up using L1 vocabulary relevant to the home and L2 vocabulary relevant to school, but this pattern may change if they move out of their childhood home and become dominant in the L2, using it both at home and at school. One might expect that the cognitive control needed to retrieve the word *plate* might change based on these environments, such that top-down control will become more important as the L1-usage of the word becomes more infrequent.

Regarding the use of cognitive control training as a tool to aid language acquisition, future studies would first need to identify how much training is required to affect language use and how long the effect lasts. This study trained participants for a relatively short time, only 30 minutes. However, 30 minutes spent actually practicing the vocabulary would likely have improved their performance more. Consequently, future studies should attempt to identify the limits of these effects in order to determine both a) whether they should and b) if they can, be translated into a more applied setting.

Chapter 4: General Discussion

This dissertation sought to extend the conceptual distinction that the cognitive control literature makes between bottom-up and top-down inhibition to the language-learning domain (e.g. Verbruggen & Logan, 2009; Spierer et al., 2013). The goal of this extension was to improve the understanding of adult L2 learning by targeting the relationship between L2 proficiency and cognitive control, which is currently subject to competing hypotheses in the literature: the BIA-d and Convergence Hypothesis (Grainger, Midgeley & Holcomb, 2010; Green, 2003). By associating differential control processes with proficiency of language learning, I hoped to reconcile these competing hypotheses such that we can consider the predictions of the BIA-d to apply to bottom-up control, and those of the CH to apply to top-down control. Specifically, I predicted that higher proficiency learners would be more likely to have developed automatic inhibitory responses between L2 words and their L1 translation, allowing for bottom-up control. Based on previous work (Manuel et al., 2013; Manuel et al., 2010) I expected that the use of bottom-up control would distinguish itself via greater activity in temporo-parietal motor control regions and less activity in prefrontal cortex. Furthermore, I predicted that lower proficiency learners would be more likely to rely on top-down control when reading or retrieving words in the L2, as evidenced by greater activity in prefrontal cortex and particularly rostral aspects of IFG (i.e., pars orbitalis; Uddin et al., 2011). I expected that these findings would allow for further specification, and consequently reconciliation, of the BIA-d and CH (Grainger, Midgeley & Holcomb, 2010; Green, 2003).

To test these hypotheses I conducted two experiments. The first used fMRI to examine low and high proficiency Spanish learners while they completed a semantic decision task in both languages, as well as the Go/No-go and Stop-Signal tasks, which are known to elicit bottom-up and top-down control, respectively. The second experiment built on Experiment 1 and used a training paradigm to investigate if there was a causal relationship between L2 semantic processing and cognitive control. Specifically, I expected that training top-down control, but not bottom-up control, would affect semantic processing, particularly for low proficiency learners who I hypothesized would rely more on top-down control.

Experiment 1. The results of Experiments 1 are supportive of my predictions that proficiency modulates the type of cognitive control used in language processing. In Experiment 1 I found that higher L2 proficiency was associated with reduced activity in the CN, as well as increased activity in the cerebellum and right STG for words in the L2 as compared to in the L1. Furthermore, a multivariate decoding analysis found that patterns of activity in the left CN, ACC, and IFG pars triangularis best distinguish between high proficiency and low proficiency learners. I additionally observed that the connectivity between the high and low proficiency learners differed in efficiency, with high proficiency learners relying on an ordered loop structure from abstract to motor processing, and low proficiency learners' networks being characterized by redundant connections.

The overall pattern of results from this study, although it does not exactly conform to my predictions, is indicative of differential control use by high and low proficiency learners. The CN, for example, is the nucleus of the basal ganglia that is most commonly associated with executive control. Braunlich and Seger (2013) identify the caudate head as a critical portion of the executive corticostriatal loop, which also connects to the thalamus and dorsolateral prefrontal and posterior parietal regions. Other work by Yin and colleagues has identified the CN as being critical early in skill acquisition, while the putamen, for example, is more active once the skill has become automatized. The reduction in CN activity with increased proficiency that I observed, as well as the identification of the CN as a critical region differentiating the two groups by the classification algorithm of the decoding analysis, aligns well with my prediction and that of the Convergence Hypothesis that the use of top-down control would be reduced in higher proficiency learners.

The other half of my prediction, that top-down control would be replaced by bottom-up control, is reflected by the increase of activity in the cerebellum and STG for high proficiency learners, as well as the identification of IFG pars triangularis—a region previously implicated in bottom-up control by Lenartowicz et al. (2011)—as a critical region in the decoding analysis. Although I had predicted that bottom-up control would be reflected in increased activity in parietal, rather than superior temporal, regions relative to the low proficiency group, the STG is a neighboring region that has been previously indicated in bottom-up control. Manuel et al. (2010), for example, found that training on the Go/No-go task affected activity in temporo-parietal cortex. Their study used EEG, however, and consequently was unable to localize the source of the change further. The results of Experiment 1 suggest that the STG may be that source, and would be congruent with previous findings indicating that rSTG is involved in language control in more balanced bilinguals (see Luk, Green, Abutalebi & Grady, 2012).

My results also indicate a role for the cerebellum in bottom-up control. One previous fMRI study, conducted by Chavan and colleagues (2015), supports this hypothesis, as they found that activity in the left cerebellum reduced with training on the Go/No-go task. Furthermore, studies examining cerebellar connectivity have found that the cerebellum is contralaterally connected to association areas in the cortex, including the STG (De Smet et al., 2013). Consequently, the appearance of both the cerebellum and the STG in the higher proficiency learners suggests that they are working in concert to effect bottom-up control during language processing.

The above conclusion is congruent with the existing literature on the role of the cerebellum in language control, even if that literature does not use the term bottom-up control. Green and Abutalebi's (2013) Adaptive Control hypothesis, which builds on the Convergence Hypothesis (Green, 2003) by specifying how different patterns of language use rely on different types of cognitive control, outlines roles for the cerebellum in two contexts. It specifies that the right cerebellum is involved in dense code-switching contexts, and the cerebellum (lateralization unspecified) in salient cue detection, which they hypothesize should be brought online in dual-language contexts. Examining the other members of the salient cue detection network, specifically the inclusion of the right inferior frontal cortex, suggests that the salient cue detection network would draw specifically on the left cerebellum (due to the contra-lateral connections between the cerebellar and cortical hemispheres; see De Smet et al., 2013), which is what I observed. Given that the semantic decision task in my study was administered in language-mixed runs, one could consider the experiment to be a dual-language context. Consequently, the observed activation of the left cerebellum in my study is congruent with the predictions of the Adaptive Control model.

In addition to identifying critical regions during each pattern of language use, the Adaptive Control model also makes predictions about the connectivity between these regions (see *Figure **2***) and the GIMME connectivity analysis that I conducted included many of the Adaptive Control model's regions of interest, including the left IFC (separated into pars triangularis, opercularis, and orbitalis), the SMA, the inferior parietal cortex, and the caudate and putamen of the basal ganglia (Green & Abutalebi, 2013). In my results, I found that the frontobasal loop was used by both high and low proficient learners, as would be predicted by the Adaptive Control hypothesis given the dual language context of the study. However, the specific connections between these regions differed based on the participants' proficiency, such that higher proficiency learners showed more structured connectivity than low proficient learners. For example, the role of the SMA differed substantially between these two groups, acting as a feedback mechanism for IFG and basal ganglia in the high proficiency group, rather than a receiver of information in the low proficiency group. That difference in the direction of connectivity is not predicted by the Adaptive Control hypothesis, which includes bilateral connections between the SMA and the basal ganglia and IFC, but does not specify the conditions leading to information flow in one direction or the other.

Furthermore, I found that the number of connections between the basal ganglia and the IFG varied between the low and high proficiency learners, such that in low proficiency learners the IFG directs the basal ganglia and in high proficiency learners the basal ganglia exert influence over the IFG (with the exception of one connection from the IFG_orb to the CN). If we consider these results with respect to the predictions of the Conditional Routing model (Stocco et al, 2014), it appears that their predictions apply only to the higher proficiency learners. As I discuss in Chapter 1, the Conditional Routing model suggests that the basal ganglia affect cortico-cortical connections during language selection in order to select the weaker language. Stocco et al.'s prediction is in contrast with non-linguistic theories of cognitive control such as the one put forward by Munakata et al. (2011), which predict that the direction of influence would be reversed, from the IFG to the basal ganglia. My results suggest that both models are partially correct, and that they apply to different situations. Future research should examine the relative roles of these feed-forward and feedback connections between the IFG and basal ganglia and the differing experimental conditions that elicit them.

The overall pattern of results from Experiment 1 suggests that top-down and bottom-up control are used differentially by high and low proficiency language learners. This pattern arises from a multi-modal analysis using univariate, multivariate, and connectivity methods, and is further supported by the results from Experiment 2.

Experiment 2. In Experiment 2, I found that training on the Stop-Signal task, which requires top-down control, but not training on bottom-up control or a sham task, significantly speeded the animacy judgments of language learners, particularly those with low L2 proficiency. This pattern of results is congruent with my prediction that lower proficiency participants would rely more on top-down control than higher proficiency participants, and consequently would benefit more from top-down control training. Although I did not see effects of training in the accuracy data, this is likely due to a) having used an outcome measure that requires recall rather than recognition memory and b) that cognitive control training typically affects reaction time, rather than accuracy, data (see Oberauer, 2005).

The results of Experiment 2 also add to a growing literature using training studies to examine the relationship between cognitive control and language processing. Previous work in the L1 domain by Novick and colleagues (2014), for example, found that training on a version of the n-back task that included lures, but not training on running span, letter-number sequencing, or block span affected participants' ability to resolve ambiguous sentences. Later work from Hussey, Harbison, Teubner-Rhodes, Mishler, Velnoskey & Novick (2016) found that training on the n-back with lures, but not an adaptive n-back task or a 3-back task, affected language processing under conditions associated with conflict, such as verb generation under conditions of both high association and competition, and the regression-path time for ambiguous but not unambiguous sentences. Similar to these studies, the results of Experiment 2 support the finding that transfer can only be achieved when the training does not allow for automatization (i.e., is top-down) and when the task to be transferred to shares some component with the trained task (i.e., the need for cognitive control in L2 or ambiguous sentence processing).

The results of Experiment 2 also build on the only existing study to examine the effect of control training on L2 processing, conducted by Liu et al. (in press). Liu et al. trained low inhibitory control participants on the Simon task and found that the training led to language switching patterns more similar to their high inhibitory control participants. The current study builds on these data by examining the role of cognitive control training during L2 processing specifically, as opposed to language switching. It also represents a significant methodological improvement, as all participants in Experiment 2 underwent some form of training, whether top-down, bottom-up, or sham, whereas Liu et al. only trained the participants that they identified as having relatively lower inhibitory control.

In total, the results from Experiments 1 and 2 suggest that the distinction Verbruggen and colleagues (2014) and Spierer et al. (2013) make between top-down and bottom-up control is highly relevant for research on language learning. Consequently, the data from these experiments have the possibility to extend current models of bilingual language control and processing, such as the Convergence Hypothesis (Green, 2003) and the BIA-d (Grainger et al., 2010). Specifically, through the application of the distinction between bottom-up and top-down control, the conflict between these two models' predictions of when inhibition is used in language learning may be reconciled. This would require a change to the current conception of inhibition in the BIA-d, which the authors hypothesize to be directed by the L2 language node (see Figure 4 of Grainger, Midgeley & Holcomb, 2010). A more "bottom-up" reading of the hypothesis would require inhibition to be enacted at the form level, likely via a selective attention mechanism as specified by Verbruggen & Logan (2014).

Of course, adjusting the current inhibition component of the BIA-d (Grainger, Midgeley & Holcomb, 2010) to reflect bottom-up rather than top-down control would still not result in an entirely accurate model, as it would neglect the role of top-down control early in L2 acquisition. The results of this dissertation suggest that a more accurate model would include roles for both top-down and bottom-up control, and would differentially weight those based on the proficiency of the participant.

Future Directions

It is worth noting, however, that proficiency is an abstract concept and consequently the language task and the stimuli chosen may moderate how control is used during L2 processing. As I observed in Experiment 1, the difference between homographs and unambiguous second language stimuli has a significant effect on the brain regions and types of control brought online, despite being relatively equally frequent. Another possibility to test the distinction between bottom-up and top-down control in language learning would be to manipulate participants' relative mapping consistency via the frequency of the words themselves, rather than the overall proficiency of the learner. I would predict that even within highly proficient bilinguals, processing of less frequent words would require more top-down processing while more frequent words would likely engage the bottom-up control network.

Additionally, the importance of the task was highlighted by the fact that I observed patterns of activity for the unambiguous Spanish words in the high proficiency learners that were similar to those that the Adaptive Control model would predict for bilinguals in a dual language context (e.g., recruitment of the cerebellum), even though the bilinguals I recruited lived in a highly L1-dominant, single-language context. Consequently, it would be of interest for future studies to investigate whether similar distinctions between top-down and bottom-up control would arise in different linguistic and experimental contexts. Multiple theories, including Chrysikou's (2013) model of cognitive control, the Adaptive Control model (Green & Abutalebi, 2013), and even the Conditional Routing model (Stocco et al., 2014) suggest that task requirements moderate how cognitive control is recruited. For example, if the use of bottom-up control is determined primarily by proficiency, then changing the paradigm of the current experiment such that the languages were separated into unique runs would not affect the general pattern of results. In contrast, if the findings I observed were in fact due to the dual-language context I created by mixing the language blocks within runs, then the Adaptive Control hypothesis would predict that creating a more single-language context within the experiment should negate the need for salient cue detection (a key component of bottom-up control), and we would observe a pattern of results implicating the regions that Green and Abutalebi suggest underlie language control in single-language contexts: ACC, left dorsal PFC, and the IPL.

Another way to investigate the role of experimental context would be to target the predictions of the Conditional Routing model by changing the task itself, rather than the order of the runs. The Conditional Routing model suggests that simple L2 tasks may be carried out via established cortico-cortical connections, and the basal ganglia may only need to "boost" the L2 signal when performing more complicated tasks. Consequently, it is possible that a grammaticality judgment task, rather than a semantic judgment task, may have elicited connectivity patterns more in line with the predictions of that model.

Language Proficiency and Non-Linguistic Control. An additional area for further study concerns the effect of language proficiency on the use of non-linguistic control. Although this study was primarily concerned with how control is used during language processing, I also observed significant differences between the two groups of participants in Experiment 1 on their accuracy performance for the AX-CPT. Specifically, I observed that the higher proficiency learners were significantly more accurate than the lower proficiency learners. Although this effect could be due to selection factors, such as motivation or IQ, that could differ between students who advance to language classes at the 300+ level and those who are enrolled in introductory classes, the fact that the higher proficiency learners in Experiment 1 showed significantly improved performance on the AX-CPT fits in with an emerging literature concerning the effects of language training on cognitive control.

Ideally, future research on this topic should examine the effects of language training in a longitudinal design. Some previous work has employed this technique, including Sullivan et al. (2014) and Zhang et al. (2015), as discussed in Chapter 1, and more recently Ramos, García, Antón, Casaponsa and Duñabeitia (2016). The results from these studies all differ, likely as a result of their differing outcome variables (the GNG, AX-CPT, and color-shape switching task, respectively) and training paradigms (Introductory Spanish for one semester, language switching for 10 days, or Introductory Basque for one year, respectively). In the Sullivan et al. (2014) study, the authors observed neurophysiological, but not behavioral, changes on the GNG task after one semester of Spanish compared to one semester of Introductory Psychology. In the Zhang et al. (2015) study, language-switching training resulted in both behavioral and electrophysiological changes during the AX-CPT, while the Ramos et al. (2016) study did not observe any behavioral changes and did not collect neuroimaging data. Clearly, more work is needed to understand this pattern of results.

The findings from this dissertation, in conjunction with those from the Zhang et al. (2015) study, suggest that the AX-CPT may be a particularly sensitive measure to the effects of language training. The AX-CPT differs from the GNG or the color-shape switching task in that it is a measure of complex executive function, requiring participants to not only inhibit or switch but also to retain information in working memory. This complexity is similar to the requirements inherent in language processing, which incorporates aspects of retrieval, working memory, and inhibition even when processing in only one language. Furthermore, the results of the conjunction analyses in Experiment 1 suggest that memory may be an area of particular overlap between language and cognitive control, supporting the possibility that the combined memory and executive components of the AX-CPT may be what makes it sensitive to the effects of language training. Consequently, future work that investigates the relationship between language training and cognitive control should consider using the AX-CPT as an outcome measure; at a minimum the replication of an outcome measure across studies would make them both more comparable and interpretable.

Conclusions

To date, the concept of cognitive control as it has been applied to language processing has focused on top-down inhibitory mechanisms, leading to conflicting predictions regarding the role of control in L2 learners at different stages of proficiency. The application of the concept of bottom-up control, as demonstrated in this dissertation both behaviorally and in terms of its accompanying neural correlates, has the potential to reconcile these competing predictions. The experiments presented in this dissertation not only demonstrate that high and low proficiency learners draw on brain regions and networks associated with top-down and bottom-up control differently, or that top-down control training is particularly advantageous for low proficiency learners, they also pinpoint the aspects of cognitive control that are shared across linguistic and non-linguistic domains, including memory and attention. Understanding these commonalities has important implications not only for the understanding of second language learning and processing, but also how we can understand language processing in the context of the brain as a whole.

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Appendix A: Stimuli in the Semantic Decision Task

English			*Spanish*			*Homograph*		
Word	***Frequency***	***Length***	***Word***	***Frequency***	***Length***	***Word***	***Frequency***	***Length***
accordion	0.866	9	anillo	15	6	alumno	11	6
acorn	2	5	año	342	3	aspiradora	0.533	10
anvil	0.734	5	bebida	12	6	barrio	74	6
backpack	0.377	8	bolígrafo	6	9	bata	12	4
beard	9	5	bolsa	40	5	billetera	0.355	9
bee	5	3	borrador	6	8	boda	23	4
bicycle	8	7	cena	37	4	calle	238	5
clown	4	5	cesto	4	5	collar	6	6
file	60	4	cine	123	4	cuadro	60	6
forest	73	6	cuaderno	14	8	falda	22	5
heel	8	4	escritorio	10	10	flor	33	4
knife	26	5	guante	8	6	gemelo	4	6
lizard	2	6	hija	116	4	joya	5	4
onion	7	5	hoja	26	4	lavandería	1	10
pirate	3	6	juguete	5	7	librería	6	8
rocket	6	6	lápiz	7	5	pan	54	3
scarf	5	5	libro	193	5	papa	36	4
scorpion	1	8	mochila	3	7	pariente	11	8
shrub	3	5	mujer	491	5	periódico	101	9
slipper	1	7	nieto	15	5	sala	8	4
sock	2	4	ojo	71	3	silla	48	5
swing	19	5	oro	90	3	ventana	93	7
wagon	6	5	queso	11	5	vestido	57	7
woman	224	5	traje	42	5	zona	115	4

Note. Frequency is shown as occurrences per million. Frequency data for the Spanish and Homograph words comes from the Lex-Esp corpus, while frequency for the English words comes from the BNC English corpus.

Appendix B: Chinese Stimuli from Experiment 2

Chinese Pinyin	*Image*	*Homophone Pinyin*	*Image*
aiyi	VASE	bao	DUSTPAN
baicai	SUN	bei	PEAR
che	OCTOPUS	bi	BATHTUB
chuang	SAW	dou	TOOTHBRUSH
cong	NAIL	fan	COAT
dai	ENVELOPE	gai	STOVE
dao	LEG	gou	KNOT
e	SPOON	hai	GIRL
feiji	PUMPKIN	hu	GLASS
fo	HAT	kele	CLOWN
guo	STRAWBERRY	lei	EGGS
haizi	HAND	lou	CROWN
he	RING	men	GUN
hua	FISH	san	MONKEY
jian	DRUM	shou	PLUNGER
jiao	CRIB	shu	BEAR
ka	CRAB	tou	MONEY
ke	BALL	xi	NECKLACE
keren	WINDMILL	xin	HAMMER
ku	VACUUM	yang	BADGE
li	TIRE		
lukou	SWAN		
niu	TENT		
pijiu	TOOTH		
ping	SLIPPERS		
qiche	WHISTLE		
qiu	POPCORN		
quezi	SLIDE		
sai	BOTTLE		
qiezi	ARM		
sou	CRUTCHES		
tian	GHOST		
wei	KEY		
yufa	APRON		
xiawu	LION		
xiong	MATCHES		
yu	SHOE		
ying	PENCIL		
tui	HANGER		
xian	KING		

Note. The images associated with the stimuli did not always match the true translation.

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Selected Publications and Papers in Preparation

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