

# Brain Mapping of Lexico-Semantic Functions in Bilinguals

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In a typical cognitive experiment, you may be shown an image of a dog and asked to name it. As a monolingual, you have several options: “dog” “poodle” “canine”, and so on. As a bilingual, however, your options are doubled. Consequently, how bilinguals select and utter the correct word for a particular object has been carefully studied in psycholinguistics and neurolinguistics. Many neuroimaging studies over the past several years have focused on the spatial aspect of this question, but other aspects, such as the developmental time course and differences between individuals, remain largely uninvestigated. In this article we provide a brief review of the literature, along with some pointers to new directions of research concerning individual variability and the development of lexico-semantic functions in bilinguals.

*Key words: Second language acquisition, bilingualism, longitudinal design, individual differences*

## 1. Introduction

Much of the existing neuroimaging work on lexico-semantic development has been based on psycholinguistic models from the behavioral literature. Although these models were originally developed without support from neuroimaging data, we argue that investigations into the neural correlates of second language (L2) acquisition have the ability to inform and modify such models. A full discussion of the major behavioral L2 acquisition models is outside the scope of this review, but we highlight two important models here to illustrate why and how neuroimaging studies may inform

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psycholinguistic models. Specifically, we examine the developmental Bilingual Interactive Activation model (Grainger, Midgeley & Holcomb, 2010; henceforth BIA-d) and the Convergence Hypothesis (Green, 2003; hereafter CH).

The BIA-d is based on two previous behavioral models: the Revised Hierarchical Model (Kroll & Stewart, 1994; RHM) and the BIA model (Dijkstra & Van Heuven, 1998). The RHM assumes that adult L2 learners create form-based connections between their first language (L1) and second language (L2), and consequently must access the concepts for L2 words via their L1, although the use of this connection changes with increasing proficiency such that more proficient bilinguals develop direct connections between L2 forms and concepts, in addition to the L1-L2 form connection. In contrast with the RHM, the computationally based BIA model (Dijkstra & Van Heuven, 1998) focuses on the processes involved in bilingual visual word recognition, the most pertinent of which for our discussion is the mechanism of inhibition. The developmental variant of this model proposed by Grainger, Midgeley and Holcomb (2010) specifically focuses on the development of inhibitory connections between form-level translation equivalents, which they argue allows for easier production of L2 forms. According to the BIA-d, inhibitory processes are more important at later, rather than earlier, stages of L2 lexical development, when more L2 words become acquired by the bilingual.

The BIA-d was one of the first L2 lexical acquisition models to consider the role of inhibition. Previous models of bilingual language processing, however, such as Green's (1998) inhibitory control model had already begun to link the language and cognitive control systems. The inhibitory control model of bilingual language processing hypothesizes that the supervisory attentional system (SAS) plays a role when automatic control is insufficient. Specifically, Green suggests that the bilingual lexico-semantic system interacts with several other components during bilingual production, including a conceptualizer, the SAS, and language task schemas. Although Green's model does not speak to L2 acquisition directly, the same idea of cognitive control is present in the convergence hypothesis (CH), especially as it is discussed by Abutalebi and Green (2007). The CH proposes that given sufficient time and practice, the L2 system will come to converge

with L1 system, rather than relying on separate neural substrates (Green, 2003). Abutalebi and Green (2007) propose that the initial difference between L1 and L2 processing is in greater engagement of the control system for L2 processing. They describe the language control system as comprising the following major areas: the prefrontal cortex (PFC), the anterior cingulate cortex (ACC), the basal ganglia, and the inferior parietal lobule (IPL). Moreover, they propose that the degree of control system engagement is moderated by L2 proficiency, such that highly proficient L2 learners should need to draw on the control system less, as the L2 for these learners should instead be converging with the L1 system. This prediction suggests that inhibition is more critical earlier, rather than later, in L2 lexical development, which contrasts with the prediction of the BIA-d model. Before turning to some of the neuroimaging data that may shed light on these predictions, we will first introduce some of our primary regions of interest that we will refer to throughout our review.

The neural networks involved in L2 processing and cognitive control overlap significantly, as Abutalebi and Green (2007) note. The PFC plays a critical role in both of these processes, although this role varies across the sub-regions of PFC. The left inferior frontal gyrus (IFG), for example, has been shown to be active both in conditions requiring lexical selection (e.g. Van Heuven, Schriefers, Dijkstra & Hagoort, 2008) and in conditions requiring non-linguistic executive control (see Garbin et al., 2010). The right IFG, however, is more typically activated in situations requiring non-linguistic executive control (e.g. Garbin et al., 2010; Bari & Robbins, 2013) although it may also be activated and even structurally affected by second language learning (see Hosoda, Tanaka, Nariai, Honda & Hanakawa, 2013; Stein et al., 2009). Another area in the PFC, the middle frontal gyrus (MFG), although typically associated with executive control and specifically working memory (e.g. Fusser et al., 2012; McNab et al., 2008), may also be co-opted during L2 acquisition (see Isel, Baumgaertner, Thrän, Meisel & Büchel, 2010; Jeong et al., 2010; Mårtensson et al., 2012).

In addition to these lateral prefrontal areas, studies of both cognitive and bilingual language processing have indicated the importance of medial and subcortical structures such as the ACC and basal ganglia. The ACC, for example, has been implicated in diverse executive control tasks (see

Badre & Wagner, 2004; Milham et al., 2001; Niendam et al., 2012) but also in L2 processing, both structurally (see Abutalebi et al., 2012; Hosoda et al., 2013) and functionally (e.g. Bradley, King & Hernandez, 2013; Guo, Liu, Misra & Kroll, 2011; Raboyeau et al., 2010). The basal ganglia, which can be further subdivided into the striatum (caudate and putamen), globus pallidus, substantia nigra, nucleus accumbens, and subthalamic nucleus, are similarly implicated across domains, although the areas most associated with language processing are those within the striatum, the caudate nucleus (CN) and the putamen. The putamen is often implicated in language production and articulation (e.g. Meschyan & Hernandez, 2006; Price, 2010) as well as cognitive control (see Niendam et al., 2012). The CN is typically implicated in cognitive control (Niendam et al., 2012; Piai et al., 2013) and language switching as opposed to production. Furthermore, the CN has been associated with L2 processing using both structural (Hosoda et al., 2013; Schlegel, Rudelson & Tse, 2012; Zou, Ding, Abutalebi, Shu & Peng, 2012) and functional measures (for a review see Abutalebi, 2008; Tan et al., 2011).

Finally, the IPL, which encompasses both the supramarginal gyrus and the angular gyrus, has been implicated in working memory, both structurally (e.g. Takeuchi et al., 2010) and functionally (e.g. Bahlmann, Korb, Gratton & Friederici, 2012; Fusser et al., 2012; Stevens, Tappon, Garg & Fair, 2012). The IPL also plays an important role in lexical processing and lexical semantic integration (for reviews, see Binder & Desai, 2011; Price, 2010), and has been postulated as a key region for vocabulary learning (Abutalebi et al., 2015; Mechelli et al., 2004). The significant overlap in cognitive and linguistic functions of the IPL arises most likely because of the intimate relationship between working memory and lexical processing: phonological working memory, including articulatory rehearsal and the phonological store (Baddeley, 2003), is critical for the formation and maintenance of lexical representations that are utilized during the acquisition of novel words in a new language (Baddeley, Gathercole, & Papagno, 1998).

Given the above discussion of the shared brain networks involved in cognitive control and L2 processing, we now turn to longitudinal studies of the functional and structural neural correlates of L2 lexico-semantic development. We show that these types of longitudinal design provide the

best way to test competing hypotheses, such as those of the BIA-d and CH.

## 2. Neuroimaging data on second language lexical development

A surprisingly small number of studies have examined the functional correlates of lexico-semantic development in second language learners longitudinally. For our purposes, we define longitudinal studies as studies that take place over the course of at least four months.<sup>1</sup> In the study by Stein and colleagues (2009), for example, native English learners of German were tested at two time points: shortly after their arrival in Switzerland (T1), and then after 5 months of immersion experience (T2). Specifically, fMRI data were collected while the learners viewed words in their first, second, or an unknown language and would indicate via button-press if they were familiar with the word presented. Stein and colleagues found that at T1, L2 learners activated frontal areas, specifically the bilateral IFG, the left inferior frontal sulcus, and left supplementary motor area (SMA), more for German than for English words. At T2, however, following their immersion experience, the activation difference between German and English was significantly reduced. In fact, only the left inferior frontal sulcus remained significantly more active to German words. This fMRI study corroborates previous data collected by the same group on the same task using electroencephalography (EEG). When comparing responses before and after immersion, Stein et al. (2006) observed significant topographic changes during the 396-540ms interval post stimulus, and source localizations revealed that the left IFG was significantly less active during this time frame at Time 2 than it was at Time 1. These data support the idea that the cognitive control network, and especially the prefrontal cortex, is vital to second language processing. Further, they suggest that its role is critical early, rather than late, in L2 acquisition, in contrast with the predictions of the BIA-d (Grainger, Midgley & Holcomb, 2010).

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<sup>1</sup> We chose four months as a minimum length due to its functional utility (it corresponds with the length of a typical semester course), as well as the frequency with which studies are conducted at or beyond this length in the literature (see Hosoda et al., 2013; Stein et al., 2006; Stein et al., 2009)

New longitudinal data from Grant, Fang and Li (in press) similarly support the role of cognitive control early in L2 acquisition. Grant et al. tested native English speakers learning Spanish over the course of an academic year at two time points, once in the fall semester (T1) and once in the spring (T2). Learners in their study completed a language specific lexical decision task while in the scanner. They found that Spanish words recruited more activity in control areas than English words at T1, but that this difference was reduced at T2, especially in the ACC. Furthermore, connectivity analyses showed that the functional networks elicited by this task changed significantly between T1 and T2, from a frontal-focused activation pattern for control processing to a temporal-focused pattern for meaning processing. In addition, individual difference analyses suggested that while all learners recruited cognitive control at T1, only learners with less cognitive control (as assessed by performance on the flanker task) continued to utilize cognitive control areas at T2. Overall, then, these data are consistent with the predictions of the convergence hypothesis, in that we see not only a reduction in non-native recruitment of cognitive control, but an additional focus on meaning processing with increased proficiency.

McLaughlin, Osterhout, and Kim (2004) conducted another longitudinal study of lexical processing. They tested students after they received an average of 14 hours, 63 hours, and 138 hours of classroom French instruction, respectively. The participants' behavioral and event related potential (ERP) responses were recorded as they made lexical decisions to the target of a prime-target pair: word-pseudoword pairs, semantically related pairs, and semantically unrelated pairs. The authors predicted that the word-pseudoword pairs should elicit the largest N400 amplitude, followed by semantically unrelated pairs, and then by semantically related pairs. Their results showed that the participants' N400 responses showed progressively larger amplitudes for the pseudowords than the words across the three sessions, even when they could not behaviorally discriminate between the two, and larger amplitudes for the words in unrelated condition than in related condition in the second (63 hours) and third sessions (138 hours). At the third session, the learners showed an N400 pattern that was expected of native speakers. These data demonstrate both the importance of longitudinal research and also highlight how neuroimaging methods

can reveal learning-related changes that are not identifiable via traditional behavioral methods.

Due to a lack of other longitudinal functional studies specifically examining second language lexical processing, we now turn our attention to an illustrative structural imaging study (for a more general review of the structural effects of L2 learning, see Li, Legault & Litcofsky, 2014). Hosoda, Tanaka, Nariyai, Honda and Hanakawa (2013), found that individual differences in L2 vocabulary size correlated with the grey matter volume of the right IFG and connectivity between that region and other areas of the language and control networks, such as the superior temporal gyrus (STG) and CN respectively. These relationships were significant not only in an initial cross-sectional study, but also in a follow-up four-month training study. In this follow-up training study, 24 native Japanese participants were asked to learn approximately 60 English words or idioms per week for 16 weeks. After training, they found that the vocabulary training had affected both grey matter volume and white matter integrity<sup>2</sup> in regions indicated by the cross sectional study. Specifically, they found increased grey matter volume in the IFG as well as the CN, ACC, and STG, and increased integrity of the white matter connections between the IFG and the CN, as well as the dorsal pathway between the IFG and STG. These data speak once again to the importance of the control network in L2 vocabulary learning in particular, and L2 learning in general. Given the importance of cognitive control in L2 vocabulary learning, we further explore the structural and functional correlates of general L2 learning, rather than only vocabulary, with a focus on the correlates of individual differences among learners.

### **3. Individual differences in second language development**

Although the study by Hosoda et al. (2013) indicates that the control

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<sup>2</sup> White matter integrity was operationalized in this study through measures of fractional anisotropy (FA) and radial diffusivity (RD). Radial diffusivity is a measure of the diffusivity perpendicular to the axon diameter, while FA is a normalized standard diffusivity measure calculated from the eigenvectors of the diffusion tensor.

network is involved in L2 processing, without corresponding behavioral data the exact role of these structures can be difficult to interpret. One study that compared behavioral performance with neural changes was Mårtensson et al. (2012), in which native Swedish speakers were followed in an interpreter training program in one of three languages (Arabic, Dari, or Russian) over the course of one semester. They found that language learners showed significantly more growth in cortical thickness of the left MFG, IFG, and STG, as well as hippocampal volume, than a control group of medical students who did not undergo interpreter training. The researchers further found that growth in the left MFG, a critical region for cognitive control, was positively correlated with the level of struggle or difficulty that the instructors reported for each student, while growth in the right hippocampus and left STG was positively correlated with achieved proficiency. These results once again support the view that cognitive control is critical early on in L2 acquisition, although this appears to be moderated by the individual's language learning aptitude.

In addition to the MFG, other studies have found that L2 acquisition may elicit structural changes more widely throughout the brain. One illustrative example comes from Schlegel et al. (2009), who tracked white matter changes in native English speakers over nine months of classroom Mandarin Chinese instruction. The authors found that not only did learners' fractional anisotropy (FA), a measure of white matter integrity, increase significantly more than control participants over the course of the nine months, but that the degree of FA change was positively correlated with individual gains in L2 performance as assessed by instructor evaluations. Specifically, they found that the white matter tracts between left hemisphere language areas (e.g. IFG, STG) increased in FA, but also that this increase extended to the right hemisphere homologues of those areas, as well as across the corpus callosum, which serves the critical role of connecting the two hemispheres.

The data from both of these studies support the idea of language as a whole-brain process, rather than as a process limited to a few areas (e.g., Broca and Wernicke's areas) or only the left hemisphere. These data resonate with the recent movement in cognitive neuroscience in general that adopts a brain network perspective on cognition (see Bassett et al.,

2011; Bressler & Menon, 2010; Sporns, 2011). To understand the complex language network and its relationship with the cognitive control network, we need to consider the interconnected brain network in language and cognitive processing. While many initial neuroimaging studies focused on the activation of particular regions of interest in isolation, new analysis techniques allow us to investigate and hypothesize about the interactions of these regions during bilingual processing and across stages of L2 development. This increased capacity has exciting potential not only for the investigation of bilingual lexico-semantic processing in general, but also for research into individual differences in L2 acquisition by providing a new perspective on the question of “what makes a good language learner” (see Li & Grant, 2014, for a discussion).

A recent paper by Yang, Gates, Molenaar and Li (2014) attempted to answer precisely this question and found that patterns of functional connectivity in brain networks were able to differentiate successful learners from less successful learners who were trained to learn a new vocabulary in a tonal language like Mandarin Chinese (for further discussion on functional connectivity techniques, see Gates & Molenaar, 2012; Gates, Molenaar, Hillary & Slobounov, 2011). Yang et al. (2014) used Group Iterative Multiple Model Estimation (Gates & Molenaar, 2012) to examine learners' fMRI patterns at the beginning (T1) and end (T2) of a six-week training period. The researchers found a more integrated and densely connected network at T2 (i.e., after training) during tone discrimination and word-picture association judgment tasks for the successful learners, as compared with the less successful learners. Specifically, both groups of learners developed a functional connection between the middle frontal gyrus (MFG) and IFG, and between the insula (INS) at Time 2. However, only the more successful learners developed functional connections between the inferior parietal lobe (IPL) and the MFG, the IPL and the INS, the supplementary motor area (SMA) and the IFG, and the STG and MFG. In contrast to these four connections developed by the successful learners, the less successful learners only developed two other connections: one between the INS and MFG, and one between the INS and SMA. It has been previously shown that STG plays a key role in lexical tone processing and acquisition (e.g., Wong, Perrachione & Parrish, 2007), and the lack of

STG's connections with other regions is not surprising in light of the poor performance outcomes in the latter group.

More interestingly, even before the training began (T1), when the same tone discrimination task was given, the successful learners, as compared with the less successful learners, showed a better-connected brain network. Specifically, while both groups of learners engaged connections between the IFG and MFG at Time 1, only the more successful learners showed significant connections between the MFG, the INS and SMA, as well as connections between the SMA and IPL, the STG and IFG, and the INS and STG. In summary, analyses of these networks' patterns before and after learning allow us to not only characterize learning outcomes but also predict learning success. It appears that short-term lexical learning success is related to the activation of the control network in that those learners who were able to utilize the entire network were ultimately more successful than those who relied exclusively on the PFC.

The neuroimaging findings from L2 learning discussed above—that lexico-semantic functioning, especially in early second language learners, is dependent on resources outside the “typical” language network—is congruent with previous behavioral work that has examined the relationship between language learning and individual differences in other cognitive skills. In addition to cognitive control, individual differences in other abilities, such as auditory processing, can also correlate or predict second language learning success. A number of studies have provided evidence in this regard. For example, Golestani, Paus, and Zatorre (2002) asked Spanish-speaking participants to learn a non-native speech contrast (Hindi dental-retroflex contrast), and found that a faster rate of learning was related to greater white matter in parietal regions, especially in the left hemisphere. The same patterns were found by Golestani, Molko, Dehaene, LeBihan & Pallier (2007): faster learners, as compared to slow learners, showed a number of structural brain differences, in particular higher white matter density and larger white matter volume in the left Heschl's gyrus in the primary auditory cortex. The role of Heschl's gyrus as related to success in learning phonetic contrasts is highly meaningful in light of the findings from Wong et al. (2008), where successful learners of lexical tones, compared with less successful learners, showed greater gray matter volume

and a trend towards increased white matter volume in the left Heschl's gyrus. These correlations between the size of the auditory processing cortex and the performance success in L2 phonetic and tonal learning point to exciting new avenues for exploring the relationship between non-linguistic and linguistic abilities on the one hand, and the relationship between language learning and neuroanatomical correlates on the other (see Li et al., 2014 for a discussion).

#### 4. Conclusion

Neuroimaging of lexico-semantic functions in bilinguals and second language learners has the potential to not only help us evaluate current models of L2 acquisition, as illustrated here by our comparison of the BIA-d and CH models, but also to help us understand neuroplasticity and brain organization more generally. From our brief review we can learn that second language acquisition, especially in its early stages, is a whole brain process that relies on both cortical and subcortical structures, although the extent to which they are utilized varies between individuals. What determines this variation is an open area for future research. An in-depth understanding of the neurocognitive mechanisms underlying lexico-semantic functions in bilinguals will likely come from large-scale longitudinal designs, careful examination of individual differences in learning, and the use of brain-network approaches that involve innovative connectivity-based analysis techniques.

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