

## Language switching in the bilingual brain: What's next?

Arturo E. Hernandez

Department of Psychology, 126 Heyne Building University of Houston, Houston, TX 77204, United States

### ARTICLE INFO

#### Article history:

Accepted 26 December 2008

Available online 27 February 2009

#### Keywords:

Cognitive neuroscience

Language

Bilingualism

### ABSTRACT

Recent work using functional neuroimaging with early bilinguals has found little evidence for separate neural systems for each language during picture naming (Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish–English bilinguals: An fMRI study. *Neuroimage*, 14, 510–520). However, switching between languages in early bilinguals during picture naming shows increased activity in the Dorsolateral Prefrontal Cortex (DLPFC) suggesting the importance of maintaining goal related information in order to bias subsequent response selection (Braver, T. S., Barch, D. M., Kelley, W. M., Buckner, R. L., Cohen, N. J., Miezin, F. M., et al. (2001). Direct comparison of prefrontal cortex regions engaged by working and long-term memory tasks. *Neuroimage*, 14, 48–59; Cohen, J. D., Braver, T. S., & O'Reilly, R. C. (1996). A computational approach to prefrontal cortex, cognitive control and schizophrenia: Recent developments and current challenges. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 351, 1515–1527; O'Reilly, R. C., Braver, T. S., & Cohen, J. D. (1999). A biologically based computational model of working memory. In E. Akira Miyake, E. Priti Shah & et al. (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control*. (pp. 375–411); New York, NY, USA). The current study set out to test early bilinguals using a picture naming paradigm. Results revealed increased activity in the DLPFC and the superior parietal lobule during language switching compared to naming of pictures in a single language. Increased activity was also observed between early learned first and second languages. The results from single language conditions revealed differences in areas devoted to language processing such as the Superior Temporal Gyrus. However, increased activity in brain areas devoted to memory, somatosensory processing and emotion were also observed. Taken together these results replicate previous studies on language switching. They also extend studies on the neural bases of bilingualism by suggesting that early bilinguals' representation of the two languages may be mediated by neural systems not typically associated with language. The article ends by considering future directions in understanding the brain bases of language switching and single language processing in bilinguals.

© 2009 Published by Elsevier Inc.

### 1. Introduction

It has now been almost 10 years since the first articles on the brain bases of language switching were published (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Price, Green, & Von Studnitz, 1999). In the first study by Price et al. (1999) a group of proficient German–English bilinguals were asked to perform a word reading task and a translation task. Words were either presented in a single language or alternated in response language. The results revealed increased activity for translation in areas involved in articulation (including the Anterior Insula and the supplementary motor area) and in attentional control including the Anterior Cingulate Gyrus. Switching on the other hand resulted in increased activity in the Broca's area and the Supramarginal Gyrus. Two separate studies conducted in our laboratory also found activation of the Dorsolateral Prefron-

tal Cortex needed for control but in a language switching condition relative to a single language condition (Hernandez et al., 2000, 2001). The task used in our laboratory involved picture naming not translation. Unpublished studies in our laboratory suggest that translation may involve a sufficiently strong executive component on its own independently of switching. Taken together these three studies revealed the recruitment of an attentional network needed to restrict retrieval of a bilingual's language. Since those studies a number of additional studies have followed up on these results (Abutalebi, Brambati, et al., 2007; Abutalebi et al., 2008; Crinion et al., 2006; Venkatraman, Siong, Chee, & Ansari, 2006; Wang, Xue, Chen, Xue, & Dong, 2007). These studies have found increased activity of brain areas involved in cognitive control when bilinguals are switching between languages.

There is one aspect that was a bit puzzling in those original studies, the almost complete lack of discussion about differences between each single language condition. In an earlier version of Hernandez et al. (2001) manuscript we even went as far as to

E-mail address: [aehernandez@uh.edu](mailto:aehernandez@uh.edu)

suggest that bilinguals two languages utilized completely overlapping neural networks with no visible difference between them. A reviewer (who I suspect was Cathy Price) rightfully pointed out that we might lack sensitivity to make these statements especially with only six subjects. This reviewer was quite correct in that a number of published studies have found evidence of differences in neural activity across a bilinguals two languages (Abutalebi, Annoni, et al., 2007; Abutalebi, Cappa, & Perani, 2001; Chee, Hon, Lee, & Soon, 2001; Chee et al., 1999; Christoffels, Firk, & Schiller, 2007; Klein, Watkins, Zatorre, & Milner, 2006; Klein, Zatorre, et al., 2006; Meschyan & Hernandez, 2006; Paulmann, Elston-Gutler, Gunter, & Kotz, 2006; Perani et al., 1998; Wartenburger et al., 2003; Xue, Dong, Jin, Zhang, & Wang, 2004). These findings suggest that differences in neural activity occur for a variety of reasons. This includes differences in age of acquisition, language proficiency and computational demands of each language (for further discussion see Perani & Abutalebi, 2005).

The current study will use the same picture naming task employed in the two seminal studies carried out in our laboratory. Hence, of particular interest to the current study are results from studies that employed a picture naming paradigm. In a seminal study, De Bleser and colleagues (2003) tested a group of Dutch-French bilinguals, who had learned French (L2) at age 10, on a covert picture naming task. Participants were asked to name pictures in each language while scanned with Positron Emission Tomography (PET). Pictures named in each language were either visually similar across languages (cognates) or visually dissimilar across languages (non-cognates). The study found increases in L2 activation relative to L1 activation in two areas of the Inferior Frontal Gyrus, BA 47 and BA 44, when naming pictures with non-cognate names. The presence of increased activity in BA 44, close to the border with BA 45, is indicative of the need for more effortful lexical selection during picture naming of non-cognates in L2 (Fiebach, Friederici, Muller, & von Cramon, 2002). Increased activity in BA 47 suggests that there is a need for more effortful semantic retrieval in a second less dominant language (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2007; Bookheimer, 2002; Poldrack et al., 1999; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001). De Bleser et al. also found increased activity in the very anterior and inferior portion of the temporal lobe. Traditionally, lesions in anterior portions of BA 20 have been associated with difficulties in retrieving the names of concrete objects (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996). More recent studies suggest that this region plays role in processing of auditory information and/or in the integration of auditory and visual information associated with nouns. The inability to access this information compromises the ability of patients with lesions in this area to produce the names of objects when elicited by visual (i.e. a picture) or sound (i.e. a ringing bell) stimuli associated with an object (Hamberger, Goodman, Perrine, & Tamny, 2001). More recent imaging studies confirm the role of this area in serving as a bridge between conceptual information and its corresponding word form. Taken together De Bleser et al. interpret their findings to indicate that naming of pictures in a second language relative to a first language involves more effortful lexical retrieval. Finally, these results are in line with other studies that have found increased activity in a bilingual's less proficient language (Abutalebi et al., 2001; Chee, Soon, Lee, & Pallier, 2004; Chee et al., 2001; Meschyan & Hernandez, 2006; Perani et al., 1996, 1998; Wartenburger et al., 2003). However, note that the precise locus of this increased activity may vary depending on the task and subject characteristics.

A second study carried out in our laboratory investigated picture naming in a group of late Spanish-English bilinguals, who had learned English later in early adulthood, were asked to name

pictures covertly in either Spanish or English while being scanned with functional Magnetic Resonance Imaging (fMRI). Picture naming in the second language (L2) relative to the native language (L1) revealed increased activity in the Right Insula, Anterior Cingulate Gyrus and Dorsolateral Prefrontal Cortex (DLPFC) and the left Fusiform Gyrus. Activity in the Anterior Cingulate Gyrus, and the DLPFC suggest that naming a picture in a late learned and less proficient L2 involves recruitment of areas involved in attentional control. Modulation of the Insula and the left Fusiform Gyrus suggests that naming in L2 involves stronger demands due to articulation and visual form processing. These results are consistent with the view that during picture naming in a second language additional cognitive control is needed in order to establish a link between an object representation and its corresponding articulatory code. In short, picture naming in L2 is in essence like a form of Stroop in which L1 codes and L2 codes compete for activation.

The studies above both involved single language contexts in which bilinguals were asked to name pictures in each of their languages. However, these two studies leave open the question of how comparisons between each language compare with those in which bilinguals are asked to switch between languages. More recently, Abutalebi et al. (2008) have addressed and extended this question. In their experiment, they tested a group of German-English bilinguals from the translation department at the University of Geneva who had learned their L2 in late childhood. The participants were asked to name pictures out loud in one of three conditions. The first two were monolingual conditions which required naming in one language with or without task switching. In the single naming condition (SNC), bilinguals were asked to produce the names of objects in one language. In a task switching condition (TSC), participants were cued to either produce the object name of a target item or to produce an associated verb. In the language switching condition (LSC), participants were cued to name objects either in L1 or L2. By using three conditions, this study would allow inferences about which neural structures distinguish between L1 and L2. Furthermore, comparison of the two switching conditions was designed to uncover which neural activity might be due to switching in general and which might be specifically due to switching between languages.

Results from this study revealed clear differences in all three conditions. First of all, naming objects in L2 differed from naming objects in L1. Increased neural activity was found in L2 in the left inferior frontal lobe, extending from the inferior portions in BA 47 up to the superior portions in BA 44. Additional activity was also observed in a wide variety of regions involved in motor control such as the bilateral Anterior Cingulate Gyrus, the left Precentral Gyrus and the Caudate Nucleus. For L1, there was only increased activity in the left Angular Gyrus.

The results also revealed interesting differences and similarities between switching within a language and switching between languages. A conjunction analysis of both switching conditions revealed increased activity in the left superior portion of IFG, including BA 44 and BA 6 as well as an inferior portion near BA 47. There was also increased activity in the bilateral Precentral Gyrus as well as the right middle and superior temporal lobe. Comparisons between the two switching conditions yielded increased activity in the between language switching condition in both superior and inferior portions of IFG. It appears that these areas are invoked when switching is required and much more so when this switching occurs across languages. In summary, switching between languages appears to involve a more effortful cognitive retrieval process than single language naming or switching within a language. The fact that this activity extends into Dorsolateral Prefrontal Cortex suggests that switching must rely, at least in part, on more executive processing.

## 2. The current study

Although studies have looked at picture naming in L1 and L2 in late learners of a second language, to date no published study has looked at this issue with bilinguals who learn both languages before the age of five. The current study seeks to fill this gap in the literature by investigating the neural correlates of covert picture naming in L1 and L2 in early Spanish–English bilinguals. These early bilinguals are of particular interest because their second language becomes their dominant language. Furthermore, their least proficient language is Spanish, their L1. Previous studies with this population have found that increased neural activity is observed for the less dominant L1 but also for the more dominant L2 (Meschyan & Hernandez, 2006). Hence, differences between the neural activity associated with L1 and L2 should be expected in the current study. Of particular interest, will be whether the less dominant L1 will reveal increased activity in areas devoted to attentional control and/or those devoted to articulation and visual word form processing. Finally, the current study will seek to extend previous work with language switching on early bilinguals. During the ensuing years, there have been numerous changes particularly in the data analysis procedures. The current study will take full advantage of these changes by employing a random effects analysis using SPM2 (Friston, Frith, Frackowiak, & Turner, 1995). Previous studies suggest that language switching relative to single language naming, leads to increased activity in areas involved in executive control, such as the Dorsolateral Prefrontal Cortex. It remains to be seen if this pattern is replicated in the current study with early Spanish–English bilinguals.

### 2.1. Method

Twelve subjects (five female and seven male) from the Santa Barbara and Los Angeles communities with a mean age of 21.4 ( $sd = 1.75$ , range 21–28) participated in the current experiment. All twelve were Spanish–English bilinguals who acquired Spanish as their first language and were exposed to English upon entering school at age five. None had any history of neurological or psychiatric disorders and had not used medication. Participants scored significantly higher on the Boston naming test in English (47) than in Spanish (32) ( $F = 10.12$ ,  $p < 0.01$ ), indicating that their dominant language was English their L2. All were right handed as assessed by our internal handedness questionnaire and reported no left handed members in their immediate family. Informed consent was obtained from all participants according to protocols approved by both the UCLA and UCSB Human Subjects Committees. All participants gave informed consent before commencing all experimental procedures.

Behavioral testing was conducted for each subject prior to the fMRI sessions. Two different sets of stimuli were used during behavioral and fMRI sessions. These two sets were matched in terms of length (1.3 vs. 1.4 syllables), frequency (55.4 vs. 72.8 parts per million), rated imageability (5.8 vs. 6.1 on an 8 point scale), and other variables which are known to influence picture naming speed and were not significantly different. No cognates were present for both behavioral and experimental stimuli.

#### 2.1.1. Procedure

Functional MRI imaging was performed with a General Electric 3.0 Tesla magnetic imager equipped with echo-planar imaging (EPI) from Advanced NMR (Wilmington, MA). For each subject, a conventional sagittal scout scan was obtained in order to determine the slices used during functional imaging. Using an EPI gradient echo sequence ( $TR = 3000$  ms;  $TE = 25$  ms; a  $64 \times 64$  scan matrix with a 24 cm FOV) 108 images were obtained for each subject over 19 slices (4 mm thick/1 mm gap). According to the atlas of

Talairach and Tournoux (1988) the most inferior and superior slices approximately corresponded to  $z = -24$  and  $z = +65$ , respectively. A set of coplanar high-resolution EPI structural images ( $TR = 4000$  ms;  $TE = 65$  ms; matrix size  $128 \times 128$ ; FOV = 20 cm) was also collected at the same time and used to spatially normalize each subject's data into a standardized template.

During functional scan sessions, lasting 5 min and 24 s, 72 simple line drawings were presented in each of four conditions. Stimuli were chosen from the Snodgrass and Vanderwart (1980) and the Pictures please catalog (Abbate, 1984). In each activation block, 18 pictures were presented at the rate of one every 2 s. Participants were shown a cue, “say” or “diga” visually for 200 ms. Participants were instructed to covertly name the picture in the language of the cue (say = English, diga = Spanish). The cue was followed immediately by the picture which was presented for 800 ms. with a 1000 ms delay prior to the next stimulus presentation. In the mixed condition, the cue switched on every picture (say, diga, say, diga) in the single language condition the cue remained the same for every picture (e.g. say, say, say for English). The order of presentation of the four blocks (two mixed, one Spanish and one English) was counterbalanced across subjects using the following randomization procedure: The blocked and mixed (M) condition appeared either as the first or last two blocks.; The Spanish (S) and English (E) conditions were counterbalanced. This yielded four versions (MMES, MMSE, ESMM, SEMM). The activation blocks alternated with five rest periods of 36 s each, during which the subjects were instructed to rest.

#### 2.1.2. Data analysis

The functional images for each subject were preprocessed and analyzed using SPM2 (Friston, 1995) which includes realignment, spatial transformation and smoothing using a 9 mm FWHM isotropic Gaussian kernel to increase the signal-to-noise ratio. Statistical random effects analyses were also conducted using SPM2 (Wellcome Department of Cognitive Neurology, Institute of Neurology, London, UK). Images were corrected for height using an uncorrected threshold value of  $p < 0.001$  and contained at least 10 contiguous voxels. Statistically significant areas were superimposed on individual brain anatomy in MNI space using SPM routines. Direct comparisons were also exclusively masked by activation vs. rest contrasts which were thresholded at  $p < 0.001$ . The masking procedure was employed in order to eliminate any voxels in which the condition of interest would be less active than the rest condition. Figures were created using the brain  $\times$  software (Kris Singh, Aston University) and a template brain from Alan Evans of the Montreal Neurological Institute (Collins, Neelin, Peters, & Evans, 1994).

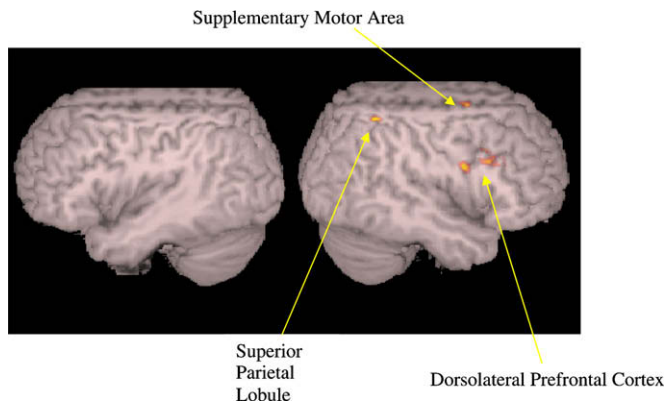
### 2.2. Results

#### 2.2.1. Behavioral data

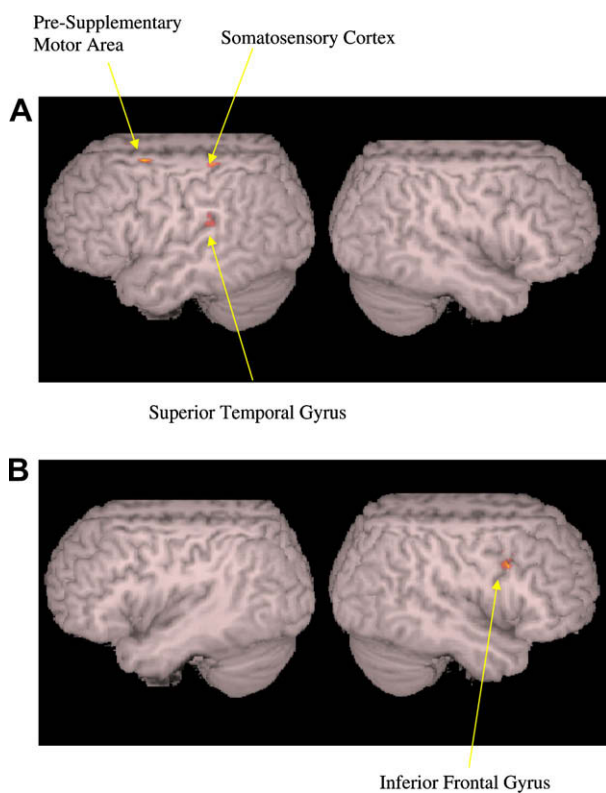
Behavioral data during pretesting of subjects were placed into a 2 (language)  $\times$  2 (blocked/mixed) condition within-subjects ANOVA. Results revealed a main effect of language in terms of percent correct,  $F(1, 11) = 11.32$ ,  $p < 0.01$  and reaction time,  $F(1, 11) = 14.85$ ,  $p < 0.01$ , such that subjects were faster and more accurate in Spanish than in English. Although the difference in reaction time between mixed and blocked condition was in the expected direction, this difference was not statistically significant ( $p < 0.08$ ) (see Figs. 1 and 2).

#### 2.3. Neuroimaging

Direct comparisons were conducted between the mixed and blocked activation conditions using the activation vs. rest comparisons as a mask (see Table 1). Mixed vs. blocked comparisons



**Fig. 1.** Areas of increased activity for the mixed relative to the blocked condition.



**Fig. 2.** Increased activity for Spanish and English single language conditions.

revealed increased activity in a network of areas including the left Superior Parietal Lobule, as well as the right Precentral Gyrus, Supplementary Motor Area, and the Dorsolateral Prefrontal Cortex. These results confirm and extend those seen in previous studies on language switching in our laboratory.

Direct comparisons between each language activation condition also revealed differences (see Tables 2 and 3). For the English vs.

**Table 2**

Areas of increased activity for English relative to Spanish.

| Region (brodmann area)       | Laterality | Voxels <sup>2</sup> | x <sup>1</sup> | y <sup>1</sup> | z <sup>1</sup> | Z    |
|------------------------------|------------|---------------------|----------------|----------------|----------------|------|
| Postcentral gyrus (BA 3)     | Right      | 50                  | 24             | −38            | 56             | 4.00 |
|                              |            |                     | 34             | −40            | 58             | 3.36 |
| Superior temporal gyrus      | Right      | 21                  | 50             | −38            | 22             | 4.08 |
| Hippocampus (CA)             | Right      | 106                 | 32             | −32            | −6             | 4.78 |
|                              |            |                     | 36             | −40            | −6             | 4.08 |
| Hippocampus (CA)             | Right      | 34                  | 36             | −12            | −14            | 3.78 |
| Insula                       | Right      | 18                  | 38             | −6             | 0              | 3.74 |
| Pre-supplementary motor Area | Right      | 57                  | 16             | 6              | 56             | 4.53 |

**Table 3**

Areas of increased activity for Spanish compared to English.

| Region (brodmann area) | Laterality | Voxels <sup>2</sup> | x <sup>1</sup> | y <sup>1</sup> | z <sup>1</sup> | Z    |
|------------------------|------------|---------------------|----------------|----------------|----------------|------|
| Hippocampus (HATA)     | Left       | 44                  | −14            | −12            | −14            | 4.44 |
|                        |            |                     | −2             | −18            | −14            | 3.62 |
|                        |            |                     | −4             | −22            | −18            | 3.18 |
| Thalamus               | Left       | 95                  | −12            | −6             | 6              | 4.15 |
|                        |            |                     | −4             | −10            | 4              | 4.01 |
|                        |            |                     | −8             | −2             | 12             | 3.68 |
| Amygdala               | Left       | 17                  | −30            | −6             | −10            | 4.04 |
| Anterior Insula        | Right      | 43                  | 28             | 12             | −14            | 4.34 |
| Inferior frontal gyrus | Left       | 52                  | −42            | 8              | 34             | 4.15 |

Spanish comparison, there was increased activity in the right Postcentral Gyrus (BA 3), Superior Temporal Gyrus, the Hippocampus, the Insula and the Pre-supplementary motor area (i.e. Frontomedian cortex). For the Spanish vs. English comparison there was increased activity in the left Hippocampus, Thalamus, Amygdala, Inferior Frontal Gyrus and the right Anterior Insula. The results from these comparisons can be seen in Fig. 2.

#### 2.4. Discussion

The current results replicate and extend previous findings in our laboratory. First, increased activity in the right DLPFC was observed in the mixed-blocked comparison, a clear replication of previous work in our laboratory (Hernandez et al., 2000, 2001). Second, the current study extends previous results by revealing increased activity of the right Precentral Gyrus, Supplementary Motor Area, and the right Superior Parietal Lobule in the mixed-blocked comparison. These results indicate a larger network that is recruited for the processing of the mixed condition than that which we reported in our original studies.

### 3. Overcoming interference during language switching

Previous studies have documented the importance of Dorsolateral Prefrontal Cortex in tasks which require the use of context in order to overcome the preponderant response (Cohen, Braver, & O'Reilly, 1996; O'Reilly, Braver, & Cohen, 1999). The current study confirms the importance of the Dorsolateral Prefrontal Cortex during language switching. These findings, however, leave open the question of why there is interference in the first place and exactly why the Dorsolateral Prefrontal Cortex is needed in order to guide the use of context.

An answer to this question can be found in the additional areas of activity found in the current study. Specifically, the supplementary motor area, superior parietal lobule and Precentral Gyrus revealed increased activity in the mixed/blocked, comparison. The supplementary motor area have been associated with motor function and have been linked to articulation and motor control in the imaging literature (Christoffels, Formisano, & Schiller, 2007; Rauschecker, Pringle, & Watkins, 2007) and has been associated with

**Table 1**

Areas of increased activity for the mixed condition compared to the blocked condition.

| Region (brodmann area)         | Laterality | Voxels <sup>2</sup> | x <sup>1</sup> | y <sup>1</sup> | z <sup>1</sup> | Z    |
|--------------------------------|------------|---------------------|----------------|----------------|----------------|------|
| Superior parietal lobule       | Left       | 34                  | −38            | −56            | 54             | 4.47 |
| Precentral gyrus               | Right      | 43                  | 48             | 2              | 28             | 4.27 |
| Supplementary motor area       | Right      | 14                  | 10             | 6              | 4              | 3.69 |
| Dorsolateral Prefrontal Cortex | Right      | 57                  | 40             | 22             | 30             | 4.62 |



the reading of words in a less proficient language (Meschyan & Hernandez, 2006). The superior parietal region has most recently been associated with language control. For example, a recent study using a reading span test revealed increased activity in the superior parietal lobule and the Dorsolateral Prefrontal Cortex in a high working memory load condition which was susceptible to intrusions (Osaka, Komori, Morishita, & Osaka, 2007). Finally, the Pre-central Gyrus has been associated with phonological retrieval (Bookheimer, 2002; Poldrack et al., 1999). Taken together these results suggest that early bilinguals recruit a set of neural areas that are involved in executive function and motor processing, articulation and phonological retrieval when naming pictures in a condition which involves language switching.

This pattern of neural activity also leaves open the question of exactly what causes the interference at the psychological level. Models in the psycholinguistic literature posit that language switching in an object naming task involves lexical selection of words in the target language and may involve inhibition of the non-target language (Costa, Caramazza, & Sebastian-Galles, 2000; Costa & Santesteban, 2004). More recent work by Costa et al. (Costa, Santesteban, & Ivanova, 2006) suggests that language switching between two highly proficient languages involves differences in lexical selection. Work by Abutalebi and colleagues (Abutalebi, Brambati, et al., 2007; Abutalebi & Green, 2007; Abutalebi et al., 2008), however, suggests that brain activity differences during language switching involves control which may reflect inhibition. Our data reveal that alternating between languages leads to activation in brain structures which play a role in executive control and articulatory and motor planning. This slowing might involve active inhibition of the non-target translation or the activation of the appropriate lexical item. Finally, the presence of activity in the Precentral Gyrus, an area involved in phonological retrieval is revealing. Specifically, it suggests that it may be interference during phonological retrieval that is the main source of interference during the mixed condition, at least for early bilinguals. Future studies with early bilinguals are needed to further disentangle whether these effects are due to lexical selection, interference across languages or both.

In our original studies, we compared mixed (alternating) vs. blocked (single language) conditions. The mixed condition clearly involves a switching component which occurs more locally because of the fact that a picture was just named in another language. In addition, the mixed condition also carries a mixing cost which occurs across the entire block of trials. In order to compare results from the current study with previous studies, the same design was used. Hence, one of the limitations of the current study is that it leaves unclear whether the need for increased executive function in early bilinguals is due to language switching and/or language mixing.

More recently, researchers have begun to look at switching costs and mixing costs separately. Studies comparing switching to non-switch trials during a mixed condition have been shown to involve increased activity in the Anterior Cingulate and Caudate Nucleus suggesting the need for increased executive function and motor processing in this condition (Abutalebi et al., 2007). The results from Abutalebi et al.'s study are compatible with the notion that bilinguals inhibit the non-target language during language switching. Future studies using picture naming are needed to confirm whether this effect also appears during picture naming with early bilinguals.

#### 4. Differences in neural activity between each language

As noted earlier, the original studies which focused mainly on language switching, contained much less discussion of the vari-

ables that modulate differences between neural activity in each language (Hernandez et al., 2000, 2001; Price et al., 1999). Since then differences in the neural activity between a bilingual's two languages has been documented extensively (Abutalebi et al., 2001; Chee et al., 2001, 2004; Meschyan & Hernandez, 2006; Perani et al., 1996, 1998; Wartenburger et al., 2003). These differences have been argued to center around modulation of the extent of activation over an overlapping neural substrate. Using the picture naming paradigm, previous studies have found that naming objects in a less proficient late learned L2, involves activation of brain areas involved in both conceptual processing and motor planning or articulation (De Bleser et al., 2003; Hernandez & Meschyan, 2006).

Work with early Spanish–English bilinguals tested in our laboratory has found that early bilinguals show increased neural activity for Spanish relative to English but also vice-versa. Meschyan and Hernandez (2006) suggest that these different patterns of neural activity could be attributed to disparities in language proficiency and/or orthographic transparency. In the current study, by asking participants to name pictures any potential orthographic differences between languages will be reduced. Increases in the least proficient language, Spanish, centered in areas dedicated to motor and speech processing. Recently, Christoffels et al. (2007) compared overt and covert naming of objects. Results revealed increased activity in the overt condition across a large network which included the Cingulate cortex, the bilateral Insula, Supplementary Motor Area, bilateral motor areas, Cerebellum, Thalamus and Basal Ganglia during feedback of verbal processing. The presence of Thalamus, Anterior Insula and Inferior Frontal Cortex near motor areas is reminiscent of the network observed by Christoffels et al. (2007). This suggests that in the less proficient language early bilinguals may be engaging in more monitoring of speech in a manner that is similar to that which occurs during overt naming in monolinguals. Future studies are needed to tease this effect out more extensively using a combination of overt and covert naming.

Increased neural activity in English relative to Spanish, on the other hand, was present in posterior areas of the brain. This included the right Posterior Insula, Hippocampus, Lingual Gyrus, and Postcentral Gyrus. The role of the Superior Temporal Gyrus has been conceptualized as assisting in sensory-motor integration during speech (Hickok & Poeppel, 2000; Hickok & Poeppel, 2004). The Postcentral Gyrus is a primary somatosensory area of the brain known to be involved in a wide range of functions. The posterior insula has been associated with introspection, the awareness of one's body (Bechara & Naqvi, 2004; Craig, 2004; Critchley, Mathias, & Dolan, 2001a; Critchley, Mathias, & Dolan, 2001b). Taken together these results suggest that when naming pictures in English, early bilinguals engage in some form of speech monitoring centered on the sensory side of the process. Although there is some motor planning that appears to be occurring it is much more higher level than the systems which are engaged in Spanish. The nature of this higher level of processing is also present in subject's awareness of their bodies and suggest that picture naming, in an early L2 even when it is the dominant language, is a more conscious process than that seen in Spanish the L1.

Additional evidence that picture naming in English involves a lesser degree of motor planning comes from increased activity in the pre-supplementary motor area. This area is highly interconnected with the Prefrontal Cortex but is not directly connected to motor areas (Luppino, Matelli, Camarda, & Rizzolatti, 1993). Hence, it is more likely to be involved in higher order planning of motor acts than the proper Supplementary Motor Area. Hence, the difference between naming pictures seem to centers on the difference in monitoring of speech for Spanish, the less proficient first language,

with a greater need for higher level planning in English, the second more proficient language.

Our results also indicated a very interesting laterality difference in activity in the hippocampus between English and Spanish. Specifically, picture naming in English revealed increased activity in the right hippocampus whereas picture naming in Spanish revealed increased activity in the left hippocampus. The role of the hippocampus in both retrieval and storage of memories is well documented. In addition, recent studies in which participants perform semantic memory retrieval tasks have found laterality differences that correlate with different aspects of semantic memory retrieval. [Whatmough and Chertkow \(2007\)](#) recently found that right hemisphere correlated with better picture naming whereas left hemisphere correlated with better word meaning retrieval. This study also revealed increased activity in the left Parahippocampal Gyrus, an area that is associated with recognition memory ([Aggleton et al., 2005](#); [Gleissner & Elger, 2001](#)). The results shed light on potential differences between picture naming in Spanish and English. In this view, the naming of pictures in Spanish the first language would be associated with more robust word meaning retrieval. In English, the naming of pictures in early bilinguals is associated faster picture naming times but also with increased reliance on recognition memory.

Finally, picture naming in Spanish revealed an increase in activity in bilaterally in the amygdala relative to naming of pictures in English. The role of the amygdala in processing of emotion is well documented ([Garavan, Pendergrass, Ross, Stein, & Risinger, 2001](#); [Hamann, Ely, Hoffman, & Kilts, 2002](#); [Hamann & Mao, 2002](#); [Kim & Hamann, 2007](#)). These studies have found increased amygdala activity for both positive and negative emotion items. In the present study, we used stimuli of common objects (fruit, furniture) which have relatively low emotional salience. Thus it is unclear why, there would be, activity in the amygdala due to the emotional salience of the stimuli themselves. Any difference in the possible salience between Spanish, the L1, and English the L2 should be due to the way in which participants interpret these stimuli. One potential explanation may have to do with the link between early cognition and emotion ([Wolfe & Bell, 2007](#)). Although speculative there is anecdotal evidence that people prefer to express emotion in their native language. In this view, the naming of pictures in an L1 may have an emotional valence that is not present in L2.

Taken together our results present a very unique portrait of the brain bases of picture naming in early Spanish–English bilinguals. Whereas there differences in activity in brain areas traditionally associated with language, there were also differences in brain areas associated with more general cognitive functions. This included areas devoted to memory (i.e. Hippocampus), somatosensory processing, emotion (e.g. Amygdala), and self-awareness (i.e. Posterior Cingulate). One question that remains is how to categorize these differences between picture naming in each language. Recently, [Hernandez and Li \(2007\)](#) have offered a sensorimotor hypothesis with regard to Age of Acquisition effects across multiple domains. In this theoretical framework, it is argued that early learning differs from late learning due differences in sensorimotor learning. One way to further conceptualize this is to consider later learning as involving higher level conscious processing whereas early learning is conceptualized as involving more lower-level processing. In this view, items in L1 may be more closely linked to emotional content as well as word knowledge. L2 items are linked to faster picture naming speeds but seem to involve a more “detached” mode of processing. Finally, it is very interesting that L1 effects appear as left lateralized whereas L2 effects appear as right lateralized. This fits in with the view that L2 appears to “build around” L2 even when the latter becomes more dominant later in life. These results fit in nicely with recent emergentist view which tie language acquisition in a more embodied manner ([Elman, Bates, Johnson, & Karmiloff-Smith, 1996](#); [Smith & Thelen, 2003](#)). Future studies are needed

to extend these results using language tasks which have differences in the emotional valence of items in each language.

## 5. Conclusion and future directions

The nature of language switching and its neural correlates have now been firmly established in the literature. Early studies on language switching established the Anterior Cingulate Gyrus and Dorsolateral Prefrontal Cortex as areas which are active during language switching across a variety of tasks ([Hernandez et al., 2000, 2001](#); [Price et al., 1999](#)). Studies in our laboratory have suggested that these areas are also active when naming a late less proficient L2 ([Hernandez & Meschyan, 2006](#)). With this firmly established we are left with the question of which direction to take in the future.

One area that has begun to emerge is the apparent link between bilingualism and inhibitory processing of visual attention. In a series of studies, Ellen Bialystok and colleagues have proposed that bilingualism enhances inhibitory processing across the lifespan ([Bialystok, 2006](#); [Bialystok, 2007](#); [Bialystok, Craik, & Freedman, 2007](#); [Bialystok, Craik, & Ryan, 2006](#); [Bialystok, Kroll, & de Groot, 2005](#); [Craik & Bialystok, 2005](#); [Fernandes, Craik, Bialystok, & Kreuger, 2007](#)). This effect is independent of video gaming experience ([Bialystok, 2006](#)) but may be influenced by Socioeconomic Status ([Morton & Harper, 2007](#)). Inhibitory control is an important construct that carries a great deal of weight in everyday life. Understanding the link between additional inhibitory control and its possible “strengthening” in bilinguals should be pursued in future studies. Of particular importance is the uncovering of the underlying mechanisms that create better inhibitory control in bilingual speakers. In this regard, computer modelling of these processes would be of particular interest as would a greater number of studies using neuroimaging techniques.

The second area of future study is understanding how early and late bilingualism differ from each other. The literature on bilingualism using the cognitive neuroscience approach has generally conceptualized the variables of language proficiency and age of acquisition using a static view. Our laboratory is no different in this regard. For example, a recently published study has emphasized control of language proficiency in two groups which differed in the age at which they learned Spanish ([Hernandez, Hofmann, & Kotz, 2007](#)). However, the reality is that language acquisition is the product of processes that are laid out over a protracted period of time. In this sense, bilingualism is the quintessential non-linear dynamical process. Our results suggest that early bilingualism in particular may involve differences in somatosensory processing, emotion and memory. Recent theoretical work has begun to draw attention to this conceptualization ([de Bot, Lowie, & Verspoor, 2007](#)). Neuroimaging techniques, such as fMRI, should help in this endeavor.

## Acknowledgements

This project was supported by a Grant from NIH/NICHD (5R03HD050313-02) entitled “Neural Correlates of Proficiency in Early Bilinguals”. I would like to thank Mirella Dapretto, Susan Bookheimer and John Mazziotta for assistance on various aspects of this project. I would also like to thank Fred Saab for assistance in data analysis and Vivian Valentin, Benjamin Storm, and Ann Firistine for assistance in data collection.

## References

- Abbate, M. S. (1984). *Pictures please: An articulation supplement*. Tucson: Communication Skill Builders.
- Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., et al. (2007). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex*.

- Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., et al. (2008). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex*, 18, 1496–1505.
- Abutalebi, J., Brambati, S. M., Annoni, J. M., Moro, A., Cappa, S. F., & Perani, D. (2007). The neural cost of the auditory perception of language switches: An event-related functional magnetic resonance imaging study in bilinguals. *Journal of Neuroscience*, 27, 13762–13769.
- Abutalebi, J., Cappa, S. F., & Perani, D. (2001). The bilingual brain as revealed by functional neuroimaging. *Bilingualism: Language and Cognition*, 4, 179–190.
- Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, 20, 242–275.
- Aggleton, J. P., Vann, S. D., Denby, C., Dix, S., Mayes, A. R., Roberts, N., et al. (2005). Sparing of the familiarity component of recognition memory in a patient with hippocampal pathology. *Neuropsychologia*, 43, 1810–1823.
- Badre, D., Poldrack, R. A., Pare-Blagoev, E. J., Insler, R. Z., & Wagner, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron*, 47, 907–918.
- Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia*, 45, 2883–2901.
- Bechara, A., & Naqvi, N. (2004). Listening to your heart: Interoceptive awareness as a gateway to feeling. *Nature Neuroscience*, 7, 102–103.
- Bialystok, E. (2006). Effect of bilingualism and computer video game experience on the Simon task. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie exp./cimentale*, 60, 68–79.
- Bialystok, E. (2007). Cognitive effects of bilingualism: How linguistic experience leads to cognitive change. *International Journal of Bilingual Education and Bilingualism*, 10, 210–223.
- Bialystok, E., Craik, F. I. M., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia*, 45, 459–464.
- Bialystok, E., Craik, F. I. M., & Ryan, J. (2006). Executive control in a modified antisaccade task: Effects of aging and bilingualism. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 1341–1354.
- Bialystok, E., Kroll, J. F., & de Groot, A. M. B. (2005). Consequences of bilingualism for cognitive development. In *Handbook of bilingualism: Psycholinguistic approaches* (pp. 417–432). New York, NY, US: Oxford University Press.
- Bookheimer, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review Of Neuroscience*, 25, 151–188.
- Chee, M. W., Caplan, D., Soon, C. S., Sriram, N., Tan, E. W., Thiel, T., et al. (1999). Processing of visually presented sentences in Mandarin and English studied with fMRI. *Neuron*, 23, 127–137.
- Chee, M. W., Hon, N., Lee, H. L., & Soon, C. S. (2001). Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. Blood oxygen level dependent. *Neuroimage*, 13, 1155–1163.
- Chee, M. W., Soon, C. S., Lee, H. L., & Pallier, C. (2004). Left insula activation: A marker for language attainment in bilinguals. *Proceedings of the National Academy of Sciences of the United States of America*, 101, 15265–15270.
- Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event-related brain potential study. *Brain Research*, 1147, 192–208.
- Christoffels, I. K., Formisano, E., & Schiller, N. O. (2007). Neural correlates of verbal feedback processing: An fMRI study employing overt speech. *Human Brain Mapping*, 28, 868–879.
- Cohen, J. D., Braver, T. S., & O'Reilly, R. C. (1996). A computational approach to prefrontal cortex, cognitive control and schizophrenia: Recent developments and current challenges. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences*, 351, 1515–1527.
- Collins, D. L., Neelin, P., Peters, T. M., & Evans, A. C. (1994). Automatic 3D intersubject registration of MR volumetric data in standardized Talairach space. *Journal of Computer Assisted Tomography*, 18, 192–205.
- Costa, A., Caramazza, A., & Sebastian-Galles, N. (2000). The cognate facilitation effect: Implications for models of lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, 1283–1296.
- Costa, A., & Santesteban, M. (2004). Lexical access in bilingual speech production: Evidence from language switching in highly proficient bilinguals and L2 learners. *Journal of Memory and Language*, 50, 491–511.
- Costa, A., Santesteban, M., & Ivanova, I. (2006). How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 1057–1074.
- Craig, A. D. (2004). Human feelings: Why are some more aware than others? *Trends In Cognitive Sciences*, 8, 239–241.
- Craik, F., & Bialystok, E. (2005). Intelligence and executive control: Evidence from aging and bilingualism. *Cortex*, 41, 222–224.
- Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., et al. (2006). Language control in the bilingual brain. *Science*, 312, 1537–1540.
- Critchley, H. D., Mathias, C. J., & Dolan, R. J. (2001a). Neural activity in the human brain relating to uncertainty and arousal during anticipation. *Neuron*, 29, 537–545.
- Critchley, H. D., Mathias, C. J., & Dolan, R. J. (2001b). Neuroanatomical basis for first- and second-order representations of bodily states. *Nature Neuroscience*, 4, 207–212.
- Damasio, H., Grabowski, T. J., Tranel, D., Hichwa, R. D., & Damasio, A. R. (1996). A neural basis for lexical retrieval. *Nature*, 380, 499–505.
- De Bleser, R., Dupont, P., Postler, J., Bormans, G., Speelman, D., Mortelmans, L., et al. (2003). The organisation of the bilingual lexicon: A PET study. *Journal of Neurolinguistics*, 16, 439–456.
- de Bot, K., Lowie, W., & Verspoor, M. (2007). A dynamic systems theory approach to second language acquisition. *Bilingualism: Language and Cognition*, 10, 7–21.
- Elman, J. L., Bates, E. A., Johnson, M. H., & Karmiloff-Smith, A. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA, US: MIT Press.
- Fernandes, M. A., Craik, F., Bialystok, E., & Kreuger, S. (2007). Effects of bilingualism, aging, and semantic relatedness on memory under divided attention. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie exp./cimentale*, 61, 128–141.
- Fiebach, C. J., Friederici, A. D., Muller, K., & von Cramon, D. Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience*, 14, 11–23.
- Friston, K. J. (1995). Commentary and opinion: II. Statistical parametric mapping: Ontology and current issues. *Journal of Cerebral Blood Flow and Metabolism*, 15, 361–370.
- Friston, K. J., Frith, C. D., Frackowiak, R. S. J., & Turner, R. (1995). Statistical parametric maps in functional imaging: A general linear approach. *Human Brain Mapping*, 2, 189–210.
- Garavan, H., Pendergrass, J. C., Ross, T. J., Stein, E. A., & Risinger, R. C. (2001). Amygdala response to both positively and negatively valenced stimuli. *NeuroReport*, 12, 2779–2783.
- Gleissner, U., & Elger, C. E. (2001). The hippocampal contribution to verbal fluency in patients with temporal lobe epilepsy. *Cortex*, 37, 55–63.
- Hamann, S., & Mao, H. (2002). Positive and negative emotional verbal stimuli elicit activity in the left amygdala. *NeuroReport*, 13, 15–19.
- Hamann, S. B., Ely, T. D., Hoffman, J. M., & Kilts, C. D. (2002). Ecstasy and agony: Activation of the human amygdala in positive and negative emotion. *Psychological Science*, 13, 135–141.
- Hamberger, M. J., Goodman, R. R., Perrine, K., & Tamny, T. (2001). Anatomic dissociation of auditory and visual naming in the lateral temporal cortex. *Neurology*, 56, 56–61.
- Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish–English bilinguals: An fMRI study. *Neuroimage*, 14, 510–520.
- Hernandez, A. E., Hofmann, J., & Kotz, S. A. (2007). Age of acquisition modulates neural activity for both regular and irregular syntactic functions. *Neuroimage*, 36, 912–923.
- Hernandez, A. E., & Li, P. (2007). Age of acquisition: Its neural and computational mechanisms. *Psychological Bulletin*, 133, 638–650.
- Hernandez, A. E., Martinez, A., & Kohnert, K. (2000). In search of the language switch: An fMRI study of picture naming in Spanish–English bilinguals. *Brain and Language*, 73, 421–431.
- Hernandez, A. E., & Meschyan, G. (2006). Executive function is necessary to enhance lexical processing in a less proficient L2: Evidence from fMRI during picture naming. *Bilingualism: Language and Cognition*, 9, 177–188.
- Hickok, G., & Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends In Cognitive Sciences*, 4, 131–138.
- Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*, 92, 67–99.
- Kim, S. H., & Hamann, S. (2007). Neural correlates of positive and negative emotion regulation. *Journal of Cognitive Neuroscience*, 19, 776–798.
- Klein, D., Watkins, K. E., Zatorre, R. J., & Milner, B. (2006). Word and nonword repetition in bilingual subjects: A PET study. *Human Brain Mapping*, 27, 153–161.
- Klein, D., Zatorre, R. J., Chen, J. K., Milner, B., Crane, J., Belin, P., et al. (2006). Bilingual brain organization: A functional magnetic resonance adaptation study. *Neuroimage*, 31, 366–375.
- Luppino, G., Matelli, M., Camarda, R., & Rizzolatti, G. (1993). Corticocortical connections of area F3 (SMA-proper) and area F6 (pre-SMA) in the macaque monkey. *Journal of Comparative Neurology*, 338, 114–140.
- Meschyan, G., & Hernandez, A. E. (2006). Impact of language proficiency and orthographic transparency on bilingual word reading: An fMRI investigation. *Neuroimage*, 29, 1135–1140.
- Morton, J. B., & Harper, S. N. (2007). What did Simon say? Revisiting the bilingual advantage. *Developmental Science*, 10, 719–726.
- O'Reilly, R. C., Braver, T. S., & Cohen, J. D. (1999). A biologically based computational model of working memory. In E. Akira Miyake, E. Priti Shah, et al. (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 375–411). New York, NY, USA.
- Osaka, M., Komori, M., Morishita, M., & Osaka, N. (2007). Neural bases of focusing attention in working memory: An fMRI study based on group differences. *Cognitive, Affective, and Behavioral Neuroscience*, 7, 130–139.
- Paulmann, S., Elston-Guttler, K. E., Gunter, T. C., & Kotz, S. A. (2006). Is bilingual lexical access influenced by language context? *NeuroReport*, 17, 727–731.
- Perani, D., & Abutalebi, J. (2005). The neural basis of first and second language processing. *Current Opinion in Neurobiology*, 15, 202–206.
- Perani, D., Dehaene, S., Grassi, F., Cohen, L., Cappa, S., Dupoux, E., et al. (1996). Brain processing of native and foreign languages. *NeuroReport*, 7, 2439–2444.
- Perani, D., Paulesu, E., Galles, N. S., Dupoux, E., Dehaene, S., Bettinardi, V., et al. (1998). The bilingual brain: Proficiency and age of acquisition of the second language. *Brain*, 121, 1841–1852.
- Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *Neuroimage*, 10, 15–35.

- Price, C. J., Green, D. W., & Von Studnitz, R. (1999). A functional imaging study of translation and language switching. *Brain*, 122, 2221–2235.
- Rauschecker, A. M., Pringle, A., & Watkins, K. E. (2007). Changes in neural activity associated with learning to articulate novel auditory pseudowords by covert repetition. *Human Brain Mapping*.
- Smith, L. B., & Thelen, E. (2003). Development as a dynamic system. *Trends in Cognitive Sciences*, 7, 343–348.
- Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms of name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, 6, 174–215.
- Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain: A 3-dimensional proportional system, an approach to cerebral imaging*. Stuttgart; New York: New York: G. Thieme; Thieme Medical Publishers.
- Venkatraman, V., Siong, S. C., Chee, M. W., & Ansari, D. (2006). Effect of language switching on arithmetic: A bilingual fMRI study. *Journal of Cognitive Neuroscience*, 18, 64–74.
- Wagner, A. D., Pare-Blagoev, E. J., Clark, J., & Poldrack, R. A. (2001). Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. *Neuron*, 31, 329–338.
- Wang, Y., Xue, G., Chen, C., Xue, F., & Dong, Q. (2007). Neural bases of asymmetric language switching in second-language learners: An ER-fMRI study. *Neuroimage*, 35, 862–870.
- Wartenburger, I., Heekeren, H. R., Abutalebi, J., Cappa, S. F., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron*, 37, 159–170.
- Whatmough, C., & Chertkow, H. (2007). RCBF to the hippocampal complex covaries with superior semantic memory retrieval. *Behavioural Brain Research*, 181, 262–269.
- Wolfe, C. D., & Bell, M. A. (2007). The integration of cognition and emotion during infancy and early childhood: Regulatory processes associated with the development of working memory. *Brain and Cognition*, 65, 3–13.
- Xue, G., Dong, Q., Jin, Z., Zhang, L., & Wang, Y. (2004). An fMRI study with semantic access in low proficiency second language learners. *NeuroReport*, 15, 791–796.