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Meta-analysis of the neural representation of first language and second language

Rajani Sebastian\textsuperscript{1}, Angela Laird\textsuperscript{2}, and Swathi Kiran\textsuperscript{3}

\textsuperscript{1}Department of Communication Sciences & Disorders  
University of Texas at Austin  
1 University Station, A1100  
Austin, TX 78712

\textsuperscript{2}Research Imaging Center  
The University of Texas Health Science Center San Antonio,  
San Antonio, TX 78229

\textsuperscript{3}Department of Speech Language and Hearing  
Boston University Sargent College  
635 Commonwealth Ave.  
Boston, MA 02215

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Corresponding author:

Rajani Sebastian  
CMA 2.132  
Department of Communication Sciences & Disorders  
University of Texas at Austin  
Austin, TX, 78712  
Phone: 512-207-0280  
Fax: 512-471-2957  
Email: sebastianr@mail.utexas.edu
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ABSTRACT

This study reports an activation likelihood estimation (ALE) meta-analysis of published functional neuroimaging studies of bilingualism. Four parallel meta-analyses were conducted by taking language proficiency into account. The results of the meta-analyses suggest differences in the probabilities of activation patterns between high proficiency and moderate/low proficiency bilinguals. The Talairach coordinates of activation in first language processing were very similar to that of second language processing in high proficient bilinguals. However, in the low proficient group, the activation clusters were generally smaller and distributed over wider areas in both the hemispheres than the clusters identified in the ALE maps from the high proficient group. These findings draw attention to the importance of language proficiency in bilingual neural representation.
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INTRODUCTION

The representation of multiple languages in the brain of a bilingual has been a subject of research for more than a century. Many theories exist about how the brain processes first language (L1) and second language (L2). Two general approaches were adopted in the study of the bilingual brain. The first approach has examined the effect of brain damage on language processing in individuals with bilingual aphasia (Fabbro, 1999). Clinical studies have enhanced our knowledge about the language recovery patterns after stroke in bilinguals, which has provided evidence for distinct and overlapping neuroanatomical representation of the languages in the brain. Research on parallel recovery after stroke in bilinguals suggests that for many bilinguals and polyglots, the areas involved in processing language may be the same (Albert & Obler, 1978; Fabbro, 1999). However, many researchers interpret selective or differential recovery of one or more language in bilingual or polyglots after stroke as suggesting non-overlapping cortical representation (Gomez-Tortosa et al., 1995; Junque et al., 1995 (pp. 139–176); Nilipourn & Ashayeri, 1989). These studies, however, do not provide any conclusions about specific regions in the brain that are responsible for processing one language versus the other.

Another approach to the study of the bilingual brain is of the experimental type, such as electrophysiological investigations (electrocortico stimulation during brain surgery and event-related potentials) and functional neuroimaging studies (PET and fMRI). Neuroimaging techniques such as PET and fMRI allowed a more direct and noninvasive study of the cortical representation of languages in the brain and can provide a clearer indication of neural regions that may be involved in processing of two languages. A large body of functional neuroimaging studies has been devoted to the investigation of language organization in the intact human brain.
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The application of these techniques to the study of bilingualism may enable us to investigate the role of several factors that have been considered to affect the neural organization of languages, such as age of second language acquisition and proficiency in second language.

A few reviews have examined the bilingual neuroimaging literature (Abutalebi, 2008; Abutalebi, Cappa, & Perani, 2001, 2005; Indefrey, 2006; Stowe & Sabourin, 2005). Abutalebi et al. (2005, pp. 497–515) reviewed several bilingual neuroimaging studies focusing on the role of age of second language acquisition and degree of proficiency attained in each of the languages. Using a traditional tabulation of label-reported regions, the authors found that when the degree of proficiency in bilinguals was high, a common language system appeared to be responsible for the processing of both languages. This included the left inferior frontal gyrus, superior and middle temporal gyri, the angular gyrus, and the temporal pole, a structure that seems specifically engaged by sentence and discourse level processing. Lower proficiency in L2 was associated with a more extended network of activations, including foci in the right hemisphere. The authors concluded that, when proficiency is kept constant, age of acquisition per se does not seem to have a major impact on brain representations of L2.

In another study, Stowe and Sabourin (2005) reviewed eight bilingual studies to explore whether the same language areas are used to process L2 as L1 and the extent to which it depended on age of acquisition. They looked at three different tasks: lexical semantics, syntactic comprehension and phonological processing. The results indicated that both L1 and L2 activated the same typical language areas in the left frontal and temporoparietal regions. In addition, even late language learners used the same neural substrates for L2 as used for L1. However, the neurological system which underlies language appeared to be used less efficiently for L2 as
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demonstrated by more extensive activations for L2 as compared to L1. This was observed for very early and highly proficient bilinguals as well as late bilinguals.

The conclusions draw by Stowe and Sabourin (2005) were similar to that drawn by Indefrey (2006). Indefrey (2006) analyzed the results of 30 hemodynamic experiments comparing L1 processing and L2 processing in a range of tasks. The results of the review indicated differences between L1 and L2, but only for subgroups of bilingual speakers. During word production, L1 and L2 engaged the same cortical areas, whereas L2 speakers with late L2 onset or lower proficiency recruited the left inferior frontal cortex more strongly than L1. For word level semantic processing in comprehension, L2 onset and exposure did not play a major role. By contrast, L2 onset played an important factor for activation differences related to syntactic processing in sentence comprehension.

In a recent review, Abutalebi (2008) examined the existing bilingual literature with a narrower focus on the neural correlates of grammatical and lexico-semantic processing in bilinguals. According to the author, neural differences between L1 and L2 may exist for both grammatical processing and lexico-semantic processing. These differences are particularly prominent for a weak L2 system, that is, in the initial stages of L2 acquisition and/or when L2 is processed with a non-native-like proficiency. The differences between L1 and L2 may disappear once a more ‘native-like’ proficiency is established in L2, reflecting a change in language processing mechanisms: from controlled processing for a weak L2 system (i.e., a less proficient L2) to more automatic processing.

The above-mentioned reviews suggest that neural representation in bilinguals is modulated by a number of factors, of which proficiency appears to be the most important. However, all these reviews have attempted to synthesize the literature using a
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descriptive/qualitative approach that inherently relies on author-supplied anatomical labels that may be unduly broad (e.g., left prefrontal cortex). Comparison of reported coordinates across studies can also prove challenging in that localization of a given set of coordinates to a particular neuroanatomical location is dependent on the target brain atlas and corresponding stereotaxic space in which the data set was registered.

In the present study, we build upon these prior efforts by using the recently developed activation likelihood estimation (ALE) (Eickhoff et al., 2009; Laird et al., 2005b; Turkeltaub et al., 2002) technique to carry out a quantitative, voxel-wise meta-analysis of published functional neuroimaging studies of bilingualism. A quantitative meta-analysis can provide a useful method to assess the state of the field, and to provide a plan for future research. This technique provides an unbiased, statistically-based approach to examine findings across studies, as opposed to the traditional ‘box-score’ or label-based qualitative methods (Laird et al., 2005a). Activation likelihood estimation was originally developed to identify the brain regions that were consistently activated during speech production (Turkeltaub et al., 2002) using coordinates reported by different functional imaging studies. It assumes that each study reports specific coordinates of activations, which vary due to differences associated with scanners, analyses, paradigms, and intersubject variability. The spatial distribution of these foci is analyzed to determine the regions in which activations are consistently observed, regardless of variability in study design. In activation likelihood estimation, the foci reported by each study are modeled as a probability distribution. Then a map of the whole brain is constructed, assigning to each voxel a value equal to the probability that an activation lies within the voxel. Significance of these values is determined by computing a null distribution obtained by permutation testing, correcting for multiple comparisons by controlling the false discovery rate. For example, a false discovery
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rate correction guarantees that in a set of voxels deemed significant for a test of \( a=0.05 \), the expected proportion of false positives is controlled (Laird et al., 2005b).

The ALE technique has been applied in the study of a variety of imaging areas such as of specific cognitive functions (Derrfuss et al., 2005; Krain et al., 2006; Laird et al., 2005a; McMillan et al., 2007; Owen et al., 2005; Price et al., 2005), major depressive disorder (Fitzgerald et al., 2008), attention deficit hyperactivity disorder (Ellison-Wright et al., 2008), stuttering (Brown et al., 2005), schizophrenia (Glahn et al., 2005), and obsessive compulsive disorder (Menzies et al., 2008).

In this study we quantitatively analyze the role of second language proficiency in bilingual neural representation using the ALE technique. The studies are divided into two groups based on L2 proficiency of the subjects: high proficiency group and low/moderate proficiency group. Our hypothesis is that greater proficiency in a language will be associated with a common overlapping network and with focal activation in core regions in this language network, whereas lesser proficiency in a language will be associated with a more distributed network of regions. These additional regions recruited are likely related to speech and cognitive functions. This same observation, that proficiency induces efficiency (i.e., a more circumscribed network of activation), has been made in numerous neural systems, perhaps most convincingly in studies of motor learning. The present experiment aimed to examine this issue in the context of functional neuroimaging studies of bilingualism.

METHODS

Literature search

Multiple PubMed literature searches (www.pubmed.com) were conducted to find all functional magnetic resonance imaging (fMRI) and positron emission topography (PET) studies
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on bilingualism. The search included keywords such as ‘bilingualism’, ‘first language’, second language’, neuroimaging, ‘fMRI’, and ‘PET’. In addition, the reference lists of these articles were reviewed for relevant studies not identified by the initial database search. This approach identified thirty three potential articles. We individually screened all the articles for the presence of Talairach or MNI coordinates and tabulated the studies into two groups based on the subjects’ proficiency in a second language: (1) high proficiency group, and (2) low/moderate proficiency group. The subject’s proficiency in a second language was determined based on the information provided in the methods section in each of the screened articles. Some studies used language screening questionnaire/ proficiency rating scales to determine the degree of L2 proficiency (e.g., Chee et al., 1999; Luke et al., 2002; Meschyan & Hernandez, 2006) where as, other used standardized national examination scores (e.g., Ding et al., 2003; Golestani et al., 2006). In order to ensue comparability, all the studies that classified the bilingual subjects as ‘fluent’, ‘proficient’, were grouped in the high proficiency group, and all the studies that classified the bilingual subjects as ‘less proficient than L1’, moderately proficient’, low proficient’ were grouped in the low/moderate proficiency group.

Of the thirty three neuroimaging studies, nineteen neuroimaging studies were not included in the meta-analyses study for the following reasons: (a) studies that did not report activation foci as 3-D coordinates (x, y, z) in stereotactic space (Dehaene et al., 1997; Hasegawa, Carpenter, & Just, 2002; Illes et al., 1999; Kim et al., 1997; Klein et al., 1994; Mahendra et al., 2003; Marian et al., 2003; Pillai et al., 2003), (b) studies that reported results of region of interest (ROI) analyses rather than whole brain results (Chee et al., 2000; Pillai et al., 2004), (c) studies that used bilingual switching and translation tasks (Hernandez et al., 2000, 2001; Price et al., 1999; Wang et al., 2007), (d) studies that did not compare the activation pattern of first language
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and second language processing on the same subjects (Rüschemeyer et al., 2005, 2006), (e) studies that did not present data for contrasts examining first language versus control and second language versus control (Wartenburger et al., 2003), and (f) studies that focused on prosody and phonetics since these studies investigate suprasegmental processing rather than linguistic processing (Callan et al., 2004; Gandour et al., 2007). This filtering of publications resulted in a relatively homogenous set of studies with similar fMRI methodology.

Fourteen neuroimaging studies of bilingual language processing are summarized in Table 1. Among these studies, eight studies investigated language processing in bilinguals with high L2 proficiency (Chee et al., 1999a, 2001; De Bleser et al., 2003; Ding et al., 2003; Klein et al., 1995,1999; Perani et al., 1998; Tham et al., 2005), and other six studies investigated language processing in bilinguals with moderate/low L2 proficiency (Golestani et al., 2006; Luke et al., 2002; Meschyan & Hernandez, 2006; Perani et al., 1996; Suh et al., 2007; Yokoyama et al., 2006). The tasks included word or sentence generation (Chee et al., 1999a; Golestani et al., 2006; Klein et al., 1995,1999), picture naming (De Bleser et al., 2003), word reading (Meschyan & Hernandez, 2006), semantic judgment (Chee et al., 2001; Ding et al., 2003; Luke et al., 2002), listening to stories (Perani et al., 1996, 1998), sentence comprehension (Suh et al., 2007; Yokoyama et al., 2006) and homophone matching (Tham et al., 2005). All studies reported data for several contrasts. Of these, only contrasts examining first language versus baseline and second language versus baseline were included in the present study.

Language pairs included orthographically similar languages like Spanish-English (Meschyan & Hernandez, 2006), Italian-English (Perani et al., 1996,1998), Catalan-English (Perani et al., 1998) and orthographically distant language like Mandarin-English (Chee et al., 1999a, 2000; Ding et al., 2003; Tham et al., 2005), Korean-English (Suh et al., 2007) and
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Japanese-English (Yokoyama et al., 2006).

**Meta-Analysis Procedures**

All meta-analyses were carried out using the activation likelihood estimation (ALE) technique (Turkeltaub et al., 2002) implemented in BrainMap (Eickhoff et al., 2009; Laird et al., 2005b), which was developed at Research Imaging Center of the University of Texas Health Science Center San Antonio (http://www.brainmap.org/ale). The results reported in MNI coordinates (De Bleser et al., 2003; Tham et al., 2005) were converted to Talairach space using the icbm2tal transform (Lancaster et al., 2007). Four separate meta-analyses were conducted: (1) first language processing in the high proficiency L2 group, (2) second language processing in the high proficiency L2 group, (3) first language processing in the low/moderate proficiency L2 group, and (4) second language processing in the low/moderate proficiency L2 group. In the present study, activation foci for contrasts examining first language versus baseline and second language versus baseline were included.

Each of these meta-analyses was conducted using the activation foci defined as the x, y, and z coordinate in a standard stereotactic space. Using ALE, the coordinates identified in the literature search were modeled with a three-dimensional Gaussian distribution, and their convergence across experiments was quantitatively assessed. A prespecified FWHM was not used in these analyses as in the original ALE approach (Laird et al., 2005b). Instead, a new algorithm (Eickhoff et al., 2009b) was used to model the spatial uncertainty of each focus using an estimation of the intersubject and interlaboratory variability typically observed in neuroimaging experiments. This algorithm limits the meta-analysis to an anatomically constrained space specified by a gray matter mask, and includes a method that calculates the above-chance clustering between experiments (i.e., random-effects analysis), rather than between
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foci (i.e., fixed-effects analysis) The test was corrected for multiple comparisons using the false discovery rate (FDR) algorithm (Genovese et al., 2002). Finally, the thresholded ALE map was created ($P<0.05$), and overlaid onto the “colinbrain” anatomical template normalized to Talairach space (Kuchonov et al., 2002) using the MRICron software (http://www.sph.sc.edu/comd/rorden/mricron). A minimum cluster size of 150 mm$^3$ was applied. Identification of the anatomical location of the voxels with peak probabilities was manually determined by reference to the Talairach and Tournoux atlas (Talairach & Tournoux, 1988).

RESULTS

High proficiency L2 group

The results from the ALE analysis of first language and second language processing in the high proficiency L2 group can be seen in Table 2 and Figure 1. Eight studies (Chee et al., 1999a, 2001; De Bleser et al., 2003; Ding et al., 2003; Klein et al., 1995, 1999; Perani et al., 1998; Tham et al., 2005) were included in the high proficiency L2 group meta-analyses. The language tasks included noun or verb generation (Chee et al., 1999a; Klein et al., 1995, 1999), picture naming (De Bleser et al., 2003), semantic judgment (Chee et al., 2001; Ding et al., 2003), listening to stories (Perani et al., 1998), and homophone matching (Tham et al., 2005). In total, 141 activation foci were analyzed for first language processing and 156 activation foci were analyzed for second language processing. Our meta-analyses detected significantly elevated probabilities of activation in a distributed network of brain regions primarily in the left hemisphere for both first and second language processing.

The areas of activation included the left inferior and middle frontal gyri (BA 44, 45), left superior frontal gyrus (BA 8), left precentral gyrus (BA 4), left middle and superior temporal gyri (BA 21, 22), left fusiform gyrus, (BA 37), left precuneus gyrus (BA 7), and left cerebellum.
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Additional activation was present in the right cerebellum. For both first language and second language processing in the high proficient L2 group, the clusters identified in the left frontal regions were larger than the clusters identified in the ALE maps from the left temporal and parietal regions.

*Moderate/Low proficiency L2 group*

The results from the ALE analysis of first language and second language processing in the low proficiency L2 group can be seen in Table 3 and Figure 2. Six studies (Golestani et al., 2006; Luke et al., 2002; Meschyan & Hernandez, 2006; Perani et al., 1996; Suh et al., 2007; Yokoyama et al., 2006) were included in our meta-analyses study of language processing in low/moderate proficiency L2 bilingual group. The language tasks included word reading (Meschyan & Hernandez, 2006), sentence generation (Golestani et al., 2006), sentence comprehension (Suh et al., 2007; Yokoyama et al., 2006), listening to stories (Perani et al., 1996), and semantic and syntactic judgment (Luke et al., 2002). In total, 147 activation foci were analyzed for first language processing and 122 activation foci were analyzed for second language processing.

The activation for first language processing was observed in a predominantly left lateralized network. For first language processing, frontal regions showed significantly elevated probabilities of activation in areas of left inferior and middle frontal gyri, (BA 4, 6, 44, 45, and 47). Additionally, significant elevated probabilities of activation were also identified bilaterally in the middle and superior temporal gyri (BA 21, 22), left fusiform gyrus (BA 37), left angular gyrus, (BA 39), left supramarginal gyrus (BA 40), left precuneus (BA 7), bilateral occipital lobe (BA 17), and left and right cerebellum.
Activation for second language processing was observed bilaterally. Significant elevated probabilities of activation were observed bilaterally in the left and right inferior frontal gyrus (BA 44, 45), left middle frontal gyrus (46/9), left parietal (BA 7), bilateral occipital regions (BA 17, 18), bilateral cerebellum, left cingulate gyrus (BA 24), left paracingulate gyrus (BA 32), and left superior temporal gyrus (BA 22). An interesting finding was that activation was observed in the cingulate and paracingulate gyrus for second language processing in low proficiency L2 group. Additionally, activation in the superior temporal gyrus (BA 22) barely reached significance for second language processing in the low proficiency L2 group. For second language processing, the clusters were generally smaller than the clusters identified in the other three meta-analyses.

Overlap in activation

An overlap in activation was observed for L1 and L2 in the high proficiency group and L1 in the low proficiency group. It should be noted that (see Table 2 and 3), the Talairach coordinates of activation in the fronto-temporal, temporo-parietal and occipital regions for first language processing in the low proficient group was very similar to that of the high proficient group.

DISCUSSION

Given the importance of language proficiency in bilingual neural representation, the present study conducted a meta-analyses focusing on low/moderate and high proficient bilinguals. The aim of this study was to quantitatively analyze the results of a number of neuroimaging studies done on bilingualism. We were particularly interested in the role of language proficiency on the neural representation of first language and second language. Our findings suggest that despite varying experimental tasks, there appears to be a similar pattern of
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regions involved in bilingual neural representation in high proficient bilinguals. In low proficient bilinguals, however, there are several differences between first and second language processing.

Language processing in high proficiency L2 group

Eight studies were included in our meta-analyses study of language processing in high proficient bilinguals. The Talairach coordinates of activation in the fronto-temporal, temporo-parietal and occipital regions in first language processing were very similar to that of second language processing. An interesting finding of these meta-analyses is the presence of large cluster volumes on the ALE maps in the left frontal region for both first language and second language processing. The frontal region appears to be one of those regions where different aspects of language processing interact with each other to deliver highly complex and interactive human language processing. Specifically, the frontal lobe is assumed to be related to semantic, syntactic and phonological processing (Bookheimer, 2002; Hagoort, 2005; Horwitz et al., 1998; Nakai et al., 1999; Siok et al., 2003, 2004; Tan et al., 2001a, 2003).

Increased probabilities of activation in the frontal region might be related to the tasks used in the studies included in the meta-analyses. Four out of the eight studies in the high proficient group used production based tasks which included word/verb generation (Chee et al., 1999a; Klein et al., 1995, 1999) and word naming (De Bleser et al., 2003). This argument is consistent with findings of a meta-analysis study on word production. Indefrey and Levelt (2004) identified the inferior frontal gyrus and the precentral cortex as the main regions that were activated during a variety of naming and word generation tasks, suggesting that they contribute to the “core processes of language production”. Alternatively, increased activation in this region might reflect comprehension processes as the other four studies used comprehension based tasks such as semantic judgment (Chee et al., 2001; Ding et al., 2003) listening to stories (Perani et al.,
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1998), and homophone matching (Tham et al., 2005). Several studies support the notion that the left frontal lobe specifically, the left inferior frontal gyrus supports language comprehension in addition to language production (Bookheimer, 2002; Moro, 2001; Zatorre 1996).

Another interesting finding of this meta-analysis was the increased probabilities of activation in the cerebellum. Although most work in the fMRI evaluation of language processing (semantic, phonological, and other) has demonstrated predominantly left hemispheric areas of supratentorial activation (inferior frontal gyrus, dorsolateral prefrontal cortex, superior temporal gyrus, supramarginal gyrus, etc), several studies show cerebellum is also involved in many cognitive processes including language processing (Booth et al., 2006; Desmond & Fiez, 1998; Fulbright et al., 1999). The finding of significant activation in cerebellum is consistent with other bilingual studies that have found activation in this region during language tasks (Chee et al., 2001; De Bleser et al., 2003; Marian et al., 2003; Pillai et al., 2003; 2004).

The other regions that were activated included the fusiform gyrus (BA 37), precuneus (BA 7) and the occipital cortex (BA 17/18). Previous bilingual neuroimaging studies have shown strong activation in the left fusiform gyrus when viewing visually presented words (Chee et al., 1999a, 2001; DeBleser et al., 2003; Ding et al., 2003; Tham et al., 2005). These studies suggest that fusiform region may participate in phonological decoding and semantic processing for visually presented items.

In general, although there were differences in the probabilities of activation in terms of the cluster volumes, the results of our meta-analysis confirmed our prediction that similar areas will be recruited during first language and second language processing in high proficient bilinguals. This corroborates the findings of previous bilingual neuroimaging studies that suggest both languages of a proficient bilingual recruit a common neural network (Chee et al., 2001, Illes
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et al., 1999, Perani et al., 1998).

*Language processing in moderate/low proficiency L2 group*

Six studies were included in our meta-analyses of language processing in low proficient bilinguals. The results of the meta-analyses suggest difference in probabilities of activation pattern observed between first language processing and second language processing in low proficient bilinguals. For second language processing, the clusters were generally smaller and distributed over wider areas than the clusters identified in the ALE maps from the first language processing (see Figure 2). In addition, more structures were activated in the right hemisphere and in the left hemisphere for the low proficient group compared to the high proficient group. This finding is consistent with the view that low proficient bilinguals recruit additional areas to compensate for language proficiency (Dehaene et al., 1997; Perani et al., 1996).

One finding during second language processing was that the activation in the left superior temporal gyrus barely reached significance in the low proficient group. The size of the cluster was 160 for L2 processing compared to 728 for L1 processing. Stronger activation of this area might be related to a more extensive conceptual processing associated with the larger amount of retrieved semantic information (Vandenberghe et al., 1996). It is possible that this reduced activation in the temporal region for L2 processing in the low proficient group may reflect poor semantic representation in the less proficient second language. This meta-analysis reflects the lack of temporal activations in many of the studies in the low proficient group. For example, Yokohama et al. (2006) did not find activation in the temporal region during second language processing in their low proficient L2 subjects during sentence comprehension. Similarly, Suh et al., (2007), did not find activation in their subjects who were moderately proficient in L2 during sentence comprehension. This finding draws a link between subjects with low proficiency in
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their L2 and young children who are learning a language. Studies have shown that increasing skill and learning on semantic tasks are associated with greater activation in the temporal region (Sandak et al., 2004; Shaywitz et al., 2002). Greater activation may be associated with increasing elaboration of semantic representations, i.e., a greater number of semantic representations with more interconnections between these representations. Behavioral research shows that as vocabulary knowledge increases, the child's semantic system is gradually elaborated due to the greater number of conceptual links (McGregor & Appel, 2002; McGregor et al., 2002). As reported above, we found weak activation in the left temporal lobe for L2 in the low proficiency group suggesting weaker semantic connection. L1 and L2 processing in the high proficiency group show greater probabilities of activation in the left superior temporal gyrus suggesting elaborate semantic representation and more effective semantic integration.

Another interesting finding observed in this study was the presence of increased activation in the right inferior frontal gyrus for second language processing. Clinical evidence has suggested that impairments of the left frontal region might induce contralateral areas to take over functions previously carried out by the homologues left-sided brain structures, suggesting a compensatory role for right frontal regions (Fernandez et al., 2004; Thulborn et al., 1999; Weiller et al., 1995; Winhuisen et al., 2007). Bush et al. (1999) also observed bilateral inferior frontal activation during the counting Stroop test in adults with attention deficit/hyperactivity disorder. This increased activation was attributed to enhanced cognitive effort required for subjects with ADHD. Similarly, low proficient bilinguals might recruit the right frontal regions to compensate for reduced language proficiency in L2. This argument is in line with previous findings, which have indicated the recruitment of the right hemisphere during processing of weaker second language (Luke et al., 2002; Meschyan et al., 2006; Yokohama et al., 2006).
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Increased probabilities of activation were also observed in the left prefrontal, specifically the dorsolateral prefrontal cortex (BA 46, 9) and the anterior cingulate cortex (BA 24, 32) during the less proficient L2 processing. According to Abutalebi and Green (2007), functional neuroimaging studies investigating the aspects of cognitive control confirm that cognitive control emerges from the integration of separable neural systems (Botvinick et al., 1999; MacDonald et al., 2000; Petrides et al., 1993). According to Braver et al. (2001), these systems include prefrontal, inferior parietal cortex and, anterior cingulate cortex. The prefrontal cortex is a collection of interconnected neocortical areas that sends and receives projections from virtually all cortical sensory systems, motor systems, and many subcortical structures. This region is considered to be a mechanism that facilitates the processing of task-relevant representations even in the presence of prepotent, irrelevant ones (Dehaene & Changeux, 1991; Desimone & Duncan, 1995; Miller & Cohen, 2001). Increased probabilities of activation observed during L2 processing in the prefrontal cortex might be interpreted as blocking potential prepotent responses from the stronger language (L1) when processing the weaker language (L2).

Another region that is involved in cognitive control is the anterior cingulate cortex (ACC). In contrast to the prefrontal cortex that guides response selection under conditions of response, the ACC modulates cognitive control (Bush, Luu, & Posner, 2000; Cabeza & Nyberg, 1997). Functional neuroimaging studies have shown ACC activity during tasks that engage working memory, language generation, and controlled information processing (Cabeza & Nyberg, 1997). One of its most prominent roles of ACC is detecting and signaling the occurrence of conflicts in information processing (Botvinick et al., 1999; Carter et al., 1998). The emerging view is that ACC activation is related to the degree of response conflict present in a given cognitive task (Botvinick et al., 1999; Carter et al., 1998). Further, activation in the anterior
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cingulate cortex is also linked to the attention. Kerns et al. (2004) draws a crucial relationship between ACC activation and subsequent performance. Specifically, strong ACC engagement should be followed by behavior reflecting relatively focused attention and weak ACC engagement by less focused attention. Kerns et al. (2004) also observed ACC engagement in association with errors. Interestingly, the magnitude of this error response was related to post-error performance, with higher activation associated with a relatively large slow-down in reaction times. This finding is consistent with the proposal, put forth by Botvinick et al. (1999) that post-error slowing might be a consequence of conflict monitoring.

Increased probabilities of activation observed during L2 processing in the ACC might be interpreted not only as an intrusion from the proficient L1 during language tasks in the less proficient second language but also due to increased attentional demand in L2 processing. This premise is supported by several behavioral studies that show that the nontarget language is activated and that cross-language effects appear even in situations and tasks that are purely monolingual. For example, in unbalanced bilinguals, cross-language effects of L2 on L1 were found in a purely L1 context (van Hell & Dijkstra, 2002; van Wijnendaele & Brysbaert, 2002).

Taken together, these findings suggest that processing the less proficient language is demanding and requires input from several regions that are not traditionally involved in language processing. More specifically, the results of these meta-analyses suggest that lower L2 proficiency is associated with increased probabilities of activation in dorsolateral prefrontal cortex, anterior cingulate cortex and right inferior frontal gyrus. The results of this study are mostly consistent with the bilingual neuroimaging studies that were not included in this analysis. Several of these studies found that bilinguals with a less proficient L2 showed more extensive activation in L2 than in L1 (Dehaene et al., 1997; Hasegawa et al., 2002; Kim et al., 1997; Pillai
et al., 2003, 2004) and bilinguals who were equally proficient in both languages consistently showed similar pattern of activation for both languages (Hernandez et al., 2000, 2001; Illes et al., 1999; Klein et al., 1994; Marian et al., 2003, Price et al., 1999).

Our ALE meta-analysis is also in agreement with previous reviews of bilingual brain activation studies (Abutalebi, 2008; Abutalebi, Cappa, & Perani, 2001, 2005; Indefrey, 2006; Stowe & Sabourin, 2005). It should be noted that several other factors like L2 onset, exposure, and task difference might also account for differences in bilingual neural representation in addition to bilingual language proficiency. For example, Indefrey (2006) carried out a systematic review of 30 neuroimaging experiments to examine the relative influence of the three factors (onset, proficiency, and exposure) on bilingual neural representations. The author also analyzed the variations in subject groups and tasks which might explain why some studies found differences and others did not. The results indicate that for word level production all the three factors played a role, whereas for word level semantic processing in comprehension, only proficiency played a role. By contrast, L2 onset seemed to be the most important factor for activation differences related to syntactic processing in sentence comprehension.

Due to the limited number of studies included in this analysis, the present study only focused on the role of language proficiency. Research studies also suggest that this is one of the most important factor that influences bilingual neural representation. Several studies in the literature could not be included in this analysis as they did not report their results in standard 3-D stereotactic coordinates, and only reported their findings in terms of anatomically determined regions of interest. Without the use of standardized 3-D coordinates, comparisons between these studies must rely on more subjective approaches and cannot be included in voxel-based, statistical meta-analyses such as the present study. Despite exclusion of these studies, our results
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are broadly consistent with those of qualitative reviews that included both studies with and without stereotactic coordinates.

In summary, functional neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), provide a unique window into the organization of language in neurologically intact bilinguals. How a later learned second language (L2) becomes organized in the brain, relative to the first, is an intriguing question for theoretical and practical reasons. These results further confirm the premise that greater proficiency in language recruits a more focal core language network whereas lower proficiency in language recruits a more distributed network of regions. Moreover, this findings are consistent with our previous work in bilingual aphasia rehabilitation (Edmonds & Kiran, 2006) that has shown that training the less proficient language in stroke patients results in cross language transfer to the more proficient language whereas training the proficient language does not result in cross language transfer to the weaker language. Therefore, if indeed greater proficiency induces greater efficiency, it may be worthwhile to retrain the less proficient language with the goal of strengthening the common language network. In addition, these results have clinical implications in presurgical planning affecting frontal and temporal lobe in high and low proficient bilinguals. Further studies should address the role of orthographic differences in neural representation and also the role of practice and the frequency of usage of the second language in bilingual neural representation.

Conclusion

A number of functional imaging studies have addressed the issue of cerebral representation of the two languages. The present study is the first ALE meta-analysis study on
bilingual neuroimaging. Our findings draw attention to the presence of consistent differences in the bilingual neural representation between high proficient bilinguals and low/moderate proficient bilinguals. Specifically, in the low proficient group, clusters were generally smaller and distributed over wider areas in both the hemispheres than the clusters identified in the ALE maps from the high proficient group. Another important finding of the present study is reduced activation in the temporal region during second language processing in low proficient bilinguals. This may reflect poor semantic representation in the less proficient second language. In addition, greater probabilities of activation were found not only in regions traditionally involved in language processing but also in regions known to sustain the ‘cognitive control system’, such as the prefrontal cortex and the anterior cingulate cortex.
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*NeuroImage*, 32, 477–484.

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Nakai, T., Matsuo, K., Kato, C., Matsuzawa, M., Okada, T., Glover, G. H., Moriya, T., & Inui,
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### Table 1. Fourteen neuroimaging studies of language comprehension and production

<table>
<thead>
<tr>
<th>Author</th>
<th>Languages</th>
<th>Proficiency in L2</th>
<th>L2 acquisition</th>
<th>Task</th>
<th>Baseline</th>
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<tbody>
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<td>Chee et al., 1999a</td>
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<td>High</td>
<td>High</td>
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<td></td>
<td></td>
<td>Early bilinguals</td>
<td>Fixation</td>
</tr>
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<td>Chee et al., 2001</td>
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<td>High</td>
<td></td>
<td>Group I=Early Group II=Late</td>
<td>Word generation</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td>Size judgment</td>
</tr>
<tr>
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<td>Word Naming</td>
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<td>Fixation</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Asterisk viewing</td>
</tr>
<tr>
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</tr>
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<td></td>
<td></td>
<td>Backward Japanese/infrequent vowel sounds</td>
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L1=First language, L2=Second language
Table 2. Major cluster volumes and ALE scores for first and second language processing in high proficiency L2 group

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<thead>
<tr>
<th>Volume (mm$^3$)</th>
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<td>4</td>
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Table 3. Major cluster volumes and ALE scores for first and second language processing in low/moderate proficiency L2 group

<table>
<thead>
<tr>
<th>Volume (mm$^3$)</th>
<th>ALE Values</th>
<th>x</th>
<th>y</th>
<th>z</th>
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<td>1032</td>
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<tr>
<td>464</td>
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<td>440</td>
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<td>-40</td>
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<td>-12</td>
<td>Left fusiform gyrus, BA 37</td>
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<tr>
<td>256</td>
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<td>28</td>
<td>-80</td>
<td>0</td>
<td>Right occipital gyrus, BA 18</td>
</tr>
</tbody>
</table>

|                 |             |       |       |       | Second language processing in low prof. bilinguals |
| 3536            | 0.0032      | -48   | 18    | 2     | Left inferior frontal gyrus, BA 45             |
|                 | 0.0025      | -46   | 20    | 26    | Left inferior frontal gyrus, BA 44             |
|                 | 0.0014      | -36   | 20    | 12    | Left inferior frontal gyrus, BA 47             |
| 1944            | 0.0026      | -4    | 0     | 58    | Left middle frontal gyrus, BA 46               |
|                 | 0.0022      | -12   | -4    | -56   | Left middle frontal gyrus, BA 9                |
| 1608            | 0.0031      | -34   | -60   | 42    | Left angular gyrus, BA 39                      |
| 1208            | 0.0019      | -48   | 0     | 46    | Left precentral gyrus, BA 4                     |
| 912             | 0.0019      | 28    | -62   | 42    | Right precuneus, BA 7                          |
| 840             | 0.0025      | -8    | 46    | -6    | Left paracingulate gyrus, BA 32                |
| 744             | 0.0024      | 30    | -80   | 0     | Right middle occipital gyrus, BA 18            |
| 720             | 0.0018      | 8     | -76   | -24   | Right cerebellum, Posterior lobe               |
| 536             | 0.0020      | -8    | 18    | 44    | Left cingulate gyrus, BA 24                     |
| 288             | 0.0015      | -28   | -82   | -4    | Left middle occipital gyrus, BA 18             |
| 224             | 0.0013      | 30    | 10    | 12    | Right Cerebrum.Sub-lobar.Claustrum.             |
| 200             | 0.0014      | -26   | -72   | 28    | Left precuneus, BA 7                          |
| 176             | 0.0014      | -44   | -58   | -12   | Left fusiform gyrus, BA 37                     |
| 160             | 0.0013      | -50   | -38   | -2    | Left superior temporal gyrus, BA 22            |
| 160             | 0.0012      | 50    | 18    | 20    | Right inferior frontal gyrus, BA 45            |
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Figure 1. Results for ALE meta-analyses for 8 studies in the high proficiency L2 group. Representative slices in (a) sagittal (b) coronal (c) axial views ($P < 0.05$; FDR corrected) are shown with Talairach planar coordinates above each slice. Red color represents ‘L1’ blue color represents ‘L2’, and purple color represents overlap in activation. The analysis demonstrated a primarily left-lateralized network, with an overlap in the frontal region and temporal region for L1 and L2.
Figure 2. Results for ALE meta-analyses for 6 studies in the low/moderate proficiency L2 group. Representative slices in (a) sagittal (b) coronal (c) axial views ($P < 0.05$; FDR corrected) are shown with Talairach planar coordinates above each slice. Red color represents ‘L1’ and blue color represents ‘L2’. Red color represents ‘L1’, blue color represents ‘L2’, and purple color represents overlap in activation.