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The Role of Age of Acquisition on Past Tense Generation in Spanish-English Bilinguals: an fMRI study

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Abstract

At its most basic sense, the sensorimotor/emergentist (S/E) model suggests that early second language (L2) learning is preferentially reliant upon sensory and motor processes, while later L2 learning is accomplished by greater reliance on executive abilities. To investigate the S/E model using fMRI, neural correlates of L2 age of acquisition were examined by employing a past-tense generation task on 22 L2 proficient bilinguals. Early bilinguals preferentially recruited left hemisphere sensorimotor regions involved in motoric control and articulation. In contrast, later learners, to a greater degree, engaged regions involved in executive cognitive control and lexical access. The data support the notion that early L2 learners devote neural resources to motor control during lexical retrieval. In contrast, later L2 learners recruit executive control mechanisms to generate the past tense. These data are consistent with the S/E model of bilingual language learning, and serve as an extension of cognitive control theories.

Keywords

Bilingualism; Age of Acquisition; Sensorimotor; Cognitive Control; fMRI

1. Introduction

1.1. Background

It is becoming clear that the age of second language (L2) learning alters neural activity during linguistic processing. However, there are still several issues facing this relatively nascent area of study. First, there is an ongoing debate about the exact nature of the underlying mechanisms that are responsible for such changes. Several models have been developed in an attempt to explain the functional neural differences that have been observed in bilinguals, but no consensus has been reached. A second issue facing this literature base is that many prior investigations of bilingualism have conflated L2 age of acquisition (AoA) and proficiency, factors that are known to be dissociable. In order to address these lingering questions about the way in which a bilingual's L2 (AoA) modulates brain activity, we

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compared early and late Spanish-English bilinguals, who were matched on various L2 proficiency measures, on a past-tense generation task.

Several models have been proposed as a framework for understanding the ways that L2 AoA modulates brain activity in the L2. One understudied framework of L2 AoA is the sensorimotor/emergentist (S/E) model (Hernandez, Li & MacWhinney, 2005; MacWhinney, 2004). The S/E model is a neo-Piagetian framework that incorporates theoretical and neurocognitive mechanisms in the development of language learning. A second model that has been proposed is the cognitive control model put forth by Abutalebi, Green, and colleagues (Abutalebi, 2008, Abutalebi & Green, 2007; 2008). Finally, a third is the declarative/procedural hypothesis, initially a model of memory (Cohen & Squire, 1980), that was subsequently adapted to describe the way in which bilingualism modulates neural activity (Ullman, 2001a, 2001b). These three models emphasize different brain activity patterns that help to distinguish early from late language learning.

Proponents of the S/E model posit that information acquired in the first few years of life is obtained through both sensory and motor means. More specifically, sensorimotor theorists postulate that linguistic information that is learned earlier in life is dependent upon sensorimotor analysis and the recruitment of phono-articulatory brain regions (Hernandez & Li, 2007), while later learned information preferentially recruits areas of the brain involved in semantic and executive cognitive processing (Hernandez, Hoffman & Kotz, 2007). Also contributing to the effects of sensorimotor learning within the first several years after birth is the rapid development and eventual loss of plasticity of frontal - basal ganglia circuits. This loss of plasticity results in the employment of different neurocognitive mechanisms for learning language, with greater reliance on executive and metalinguistic mechanisms for later language learning. Additionally, the effects of changes in plasticity changes also extend beyond linguistic abilities (see Hernandez & Li, 2007 for a review of the extant literature).

An extension of sensorimotor model, the emergentist theory (MacWhinney, 2004), describes the process by which a competitive interplay takes place between an individual's L1 and L2. Within this theory, the processes of neural competition, resonance between the languages, parasitism of the L2 off of the L1 and entrenchment into the neural substrate interact to determine a person's second language ability. According to emergentist theory, early learners of a second language have a less established, or entrenched, linguistic system for the L1. Thus, when an L2 is acquired, less overlap, competition, and parasitism occur for specific words and linguistic structures. In contrast, later learners of an L2 already have a well-consolidated and entrenched linguistic system in place. When these individuals begin to acquire L2, they do so using L1 as a reference. According to emergentist theorists (Hernandez, Li & MacWhinney, 2005; MacWhinney, 2004) this entrenchment and consolidation is conceptualized for cognitive processes as well as their neural underpinnings. For example, for a late bilingual trying to name an object in a second language, the name of the object is first generated in L1, and then the individual translates the name into the name for the object in L2 (Kroll, Bobb, Misra, & Guo, 2008). In using an L2, late bilinguals rely heavily on what is referred to as positive transfer and overlap of L1 information. With further practice and proficiency in L2, a larger degree of resonance between the two languages occurs; words in one language may prime the other, and vice versa. For individuals with less L2 experience or proficiency, this pattern of resonance may result in the need to employ cognitive control mechanisms.

Examples of sensorimotor language acquisition patterns have been reported in bilinguals. Hernandez et al., (2007) described increased left mid BA 44/45 activity for late relative to early Spanish-English bilinguals on a grammatical gender decision task. Similar findings have also been reported by Wartenburger, Heekeren, Abutalebi, Cappa, Villringer, et al.

(2003), who found more bilateral IFG activity for late learners relative to early learners in a grammatical judgment task. Taken together, these findings suggest that early-learned information is preferentially processed in brain regions that are felt to be important for both sensory and motor processing such as the putamen, anterior insula, inferior frontal gyrus, and motor cortices. Later acquired linguistic information is mediated through regions of the brain involved in executive functioning, such as dorsolateral prefrontal cortex, and other frontal regions such as anterior inferior frontal gyrus (BA 47). An important point to be taken from prior investigations of bilingualism is that L2 AoA appears to be more sensitive to grammatical processing (Indefrey, 2006), while proficiency is more closely linked to lexical and semantic processing. Moreover, these findings highlight that L2 AoA persists into adulthood and modulates the patterns of brain activation for grammatical processing long after the actual acquisition of the L2. The current study will use a past tense generation paradigm in order to further investigate the effect of L2 AoA on neural activity.

1.2. Alternative Viewpoints

In addition to the S/E framework, other theories and models have suggested alternative neural mechanisms that are responsible for early and late L2 acquisition. One such framework is the declarative/procedural (D/P) model advanced by Ullman and colleagues (2001a, 2001b). In the D/P model, differences between early and late L2 learning are reflective of the variable length of time that an individual uses his or her L2. This length of use results in differential neural representation of the L2 for early and late bilinguals, with early bilinguals relying on the procedural memory system to a greater degree, while late bilinguals are more dependent upon the declarative memory system. However, as late bilinguals are engaged in L2 processing across time, they should also come to use the procedural memory system to a greater extent. A second framework that carries implications for L2 AoA is the cognitive control model of Abutalebi, Green, and colleagues (Abutalebi, 2008; Abutalebi & Green, 2007; 2008). These authors posit that early and late bilinguals utilize similar regions and networks to perform tasks in L2, with additional reliance on mechanisms of motoric and cognitive control. Specifically, Abutalebi and Green hypothesize that bilinguals recruit several brain regions to assist with lexical selection and temporal sequencing of the L2. These brain regions are not felt to be important for lexical representation, but rather are critical for selection of the correct word in the L2, and for filtering or excluding other linguistic information such as the L1. In short, L2 requires more cognitive control in order to overcome processing in first language that has higher proficiency. Like the D/P model, the cognitive control model views differences between early and late acquired L2s as being due to differences in the automaticity of language that results from language proficiency.

1.3. Proficiency

As noted above, proficiency and AoA are often confounded. Hence, early and late learners of a language who differ in language proficiency do not necessarily reveal differences strictly due to AoA. A growing literature has investigated the effects of language proficiency on neural activity (e.g., Leonard, Torres, Travis, Brown, Hagler, et al., 2011; Meschyan & Hernandez, 2006; Chee, Soon, Lee, Pallier, 2004). Unfortunately, few studies have sought to investigate these AoA effects while properly controlling for proficiency. With a few exceptions, studies that have attempted to control for L2 proficiency (e.g., Tatsuno and Sakai, 2005) have used participant age or performance on the experimental task as proxy variables to account for this factor. In the current study, we matched our participant sample on a number of objective proficiency measures in order to control for the well-established neuromodulatory impact of this variable (Wartenburger et al., 2003). Thus, the results from the current study will allow us to uncover the effects that are due to AoA with proficiency controlled.

1.4. Aims and Hypotheses

In order to address questions regarding the role of L2 AoA in modulating brain activity, we evaluated the S/E model of L2 learning by observing the brain activity associated with past tense generation in two groups of bilinguals who are matched on L2 proficiency. We directly compared early and late L2 learners to investigate the role that L2 AoA plays in modulating neural activity during past tense verb generation. Based on the S/E model, one would hypothesize that early learners of an L2 will have a greater extent of brain activation in sensorimotor and motoric control regions, such as the basal ganglia (and in particular, the putamen) as well as primary and supplementary motor areas, that result from the competition effects between L1 and L2. In contrast, late L2 learners will have less brain activity in these sensorimotor brain areas relative to early learners due to the fact that L2 processing will be accomplished via the same neural networks used in L1. Further, we would hypothesize that this late acquisition group will demonstrate greater extent of brain activity in executive and semantic processing regions such as BA 47 and the DLPFC, in accord with the reduction in frontal-basal ganglia circuitry that takes place at the time period when the L2 was being acquired. Together, these results would demonstrate that effects of AoA lead to different pathways of acquisition, which result in different patterns of neural activity for past-tense generation that are independent of the objective proficiency in a second language.

2. Material and Methods

2.1. Participants

Twenty-two native Spanish speakers participated in the study (mean age = 23.18, SD = 3.61). Participants were recruited from the student population at the University of Houston. All participants were right handed, without prior diagnosis of psychological or neurological illness. Of the 22 total participants, 11 were classified as early learners of the English language (AoA ≤ 6 years; mean = 3.18, SD = 1.53, range = 1–6), and the remaining 11 were relatively late learners of English (AoA > 7 years; mean = 11.00, SD = 3.33, range = 7 – 17). Participant reported L2 AoA were as follows: 1,1,1,3,3,4,4,4,4,4,6,7,9,9,9,9,9,12,14,17,17. Participant AoA was determined through self-report, and utilization of an in house designed questionnaire that assessed the percentage of time participants used their L2 during every year of their life. Support for this cutoff between these two groups can be drawn from Perani, Abutalebi, Paulesu, Brambati, Scifo et al., (2003) and Meisel (2004), who state that age 6 or 7 is generally thought of as the cut-off between early and late AoA in bilinguals. Relative English proficiency was assessed through a variety of measures, including the standard 60 item version of the Boston Naming Test (BNT; The Psychological Corporation, 1983), and the Picture Vocabulary, Listening Comprehension and Passage Comprehension subtests of the Woodcock Language Proficiency Battery – Revised (Riverside Publishers, 1991). Participants were assessed for degree of handedness, completed a language history questionnaire, were screened for claustrophobia, and any other conditions that would have prevented them from participating in an fMRI experiment. The participants completed written informed consent procedures, approved by the Baylor College of Medicine and the University of Houston.

2.2. Stimuli

The stimuli consisted of 160 verbs taken from Bird et al. (2003) and Ullman et al. (1999). Please see Appendix 1 for a list of stimuli. One half of stimuli were regular verbs, and one half of stimuli were irregular verbs. Stimulus frequencies were acquired from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995; <http://wave.ldc.upenn.edu/Catalog/>) through the use of MCWord (Medler & Binder, 2005).

2.3 Design and Procedure

Participants were scanned using a 3.0 Tesla Siemens Allegra scanner at Baylor College of Medicine. Anatomical imaging parameters included: 192 transversal slices at 0.89 mm, voxel size = 0.96 mm × 0.96 mm × 0.89 mm, TR = 1200 ms, TE = 2.93 ms, FoV = 245mm × 214mm; in-plane resolution = 256 × 208, flip angle=12°. The functional images were EPI gradient echo, using 26 transversal slices at 4 mm thickness (0 mm overlap), voxel size 3.44 mm × 3.44 mm × 4.00 mm, TR = 2000 ms, TE = 40 ms, in-plane resolution = 64 × 64, flip angle = 90°. Statistical modeling was based on each individual subject's hemodynamic response function.

Following the consent procedures, participants were placed in the scanner and instructions were given in English. Participants were asked to covertly generate the past tense form of each of the visually presented verbs as accurately as possible. Morphological and syntactic processing are particularly sensitive to AoA (Weber-Fox & Neville, 1996), and past tense generation of verbs is a well-established task of morphological processing in the monolingual literature (Beretta, Campbell, Carr, Huang, Schmitt, et al., 2003; Dhond, Marinkovic, Dale, Witzel, & Halgren, 2003; Desai, Conant, Waldron, & Binder, 2006). Thus, past tense generation was chosen in this investigation based on these factors and its demonstrated ability to activate large portions of the brain's linguistic processing system. During the scanner task, stimuli were presented visually to the participant via a rear projection video screen and a series of mirrors, which allow the participant to view the screen placed behind their head. Jython software (Reston, Virginia) was used to present the stimuli to the participant every 6.5 – 8.5 seconds (average inter-stimulus interval = 7.51 seconds, SD = 0.72 seconds). Each stimulus was displayed for an average of 425 ms (8 ms SD). Stimuli were presented at and for irregular intervals in order to counteract expectation effects in regional cerebral blood flow. Following the scanning protocol, behavioral data were collected as participants viewed each of the stimuli again on a computer using PsyScope X (Trieste, Italy) or NEMO (Houston, Texas) software and were asked to overtly generate the past tense form of the verb in order to determine response accuracy. Covert generation was utilized so as not to introduce a movement artifact during scanning. Each participant received \$45 or extra credit in a college course for participation.

Following data collection, error trials (i.e., trials in which an incorrect past tense form of the verb was given outside the scanner) were removed from the image analysis so as not to confound the results and to remain consistent with the literature base. Very minimal differences were noted in the data if error trials were included in the imaging analyses. Imaging data were processed with SPM2 (Friston, Holmes, Poline, Grasby, Williams, et al., 1995) software running on Matlab7 (The Mathworks, Natwick, Massachusetts) on a Macintosh Pro computer. Using SPM, functional and anatomical images were realigned, smoothed, coregistered, warped, and segmented. Data was smoothed at 8 mm FWHM isotropic Gaussian kernel to increase signal-to-noise ratio. Statistical random effects analyses were also performed using SPM2 (Wellcome Department of Cognitive Neurology, Institute of Neurology, London, UK). Images were corrected for intensity using an uncorrected threshold value of $p < .001$. Regions of activation below 10 voxels were removed from the analyses. Statistical analyses of behavioral data were performed with SPSS (Chicago, IL). Two-tailed t-tests were utilized to compare behavioral performance across groups.

2.4. fMRI Analyses

In order to demonstrate the overall pattern of activity for all participants, a one group t-test was computed at $P < .001$, uncorrected, 10 voxel minimum activation threshold. One group t-tests were also completed for the early bilingual and late bilingual groups. Next, a 2×2

ANOVA was completed, using early and late bilinguals compared to regular and irregular verbs in order to investigate the effects of L2 AoA and verb regularity. Additionally, multiple regression analyses were completed using participant L2 AoA as a regressor variable, and controlling for participant gender and proficiency (using participant BNT score). Results are reported in Talairach space. We utilized SPM Anatomy Toolbox (Eickhoff, Stephan, Mohlberg, Grefkes, Fink, Amunts et al., 2005) to aid in localization of brain activity.

3. Results

3.1. Behavioral Results

All participants were administered the BNT, with the overall group mean raw score was 45.73 (SD=6.53). For individuals with English AoA 6, the mean BNT score was 44.09 (SD=5.82), while participants with AoA 7 had a mean BNT score of 47.36 (SD=6.78). Two-tailed t-test comparisons revealed no significant difference between these scores ($t(20)=1.16$, $p=.26$). A Spearman rank order correlation using participant AoA and this L2 proficiency measure revealed very little relationship between these two factors, with $r=.08$, $p=.72$. No significant between-group differences were found on any of the Woodcock Language Proficiency Battery measures, nor was L2 AoA significantly correlated with any of the test scores. Behavioral performance on the post-scanner task revealed better performance for the early bilinguals. A two-tailed t-test comparison revealed differences between the two groups in the post-scan behavioral measure of past-tense verb generation ($t(20) = 2.58$, $p = .02$). Please see Table 1 for all behavioral performance data.

3.2 Imaging Results

3.2.1. Past Tense Generation—As seen in Figure 1 and as outlined in Table 2, for all participants combined, generation of the past tense forms of verbs relative to rest in a one group t-test revealed areas of activity across the left hemisphere pre-central and post-central gyri, as well as left hemisphere supplementary motor regions, and right hemisphere frontal and temporal regions. Small volume correction (SVC) at $p < .05$ applied to a 10 mm spherical region in BA 44 (using coordinates from Hernandez et al., 2007, at $x=-52$, $y=-2$, $z=10$), revealed a 192 voxel region of activation ($Z=3.11$). In a one-group t-test analysis, early bilinguals demonstrated activations in primarily left hemisphere cortical and subcortical sensory and motor regions including the post-central gyrus, insula, SMA, and pallidum. In the corresponding analysis, late bilinguals demonstrated similar activations in left post-central gyrus as well as left middle cingulate, hippocampus, and other regions.

3.2.2 Cross Group Comparisons for all Stimuli

3.2.2.1. Early > Late Bilinguals, Past Tense Verb Generation: The question to be addressed by this data is the role of L2 AoA in sequential bilinguals. As seen in Figure 2, and as outlined in Table 3, the main effect of AoA, collapsing across stimulus type (i.e., all verb stimuli combined) revealed areas of activity spread throughout frontal-temporal regions for early bilinguals > late bilinguals. Specifically, large areas of activity were noted in left hemisphere motor control and language regions including the left insula extending into the left pre- and post-central gyri, left superior temporal gyrus (STG) extending into the left supramarginal gyrus and left middle temporal gyrus, left putamen and thalamus, and left supplementary motor area (SMA). Smaller areas of activity were noted in the right middle temporal gyrus extending into superior temporal gyrus, left superior occipital gyrus, right precentral gyrus, right calcarine gyrus, right lingual gyrus, right middle cingulate, left inferior parietal lobule and right thalamus. When run as a multiple regression analysis (controlling for proficiency and participant gender) for all subjects grouped together, earlier

L2 AoA correlated with a region of activation in the left hemisphere SMA (corresponding to the cross-group analysis: 119 voxels, Z-value = 3.81, peak of activity: $x=-5$, $y=4$, $z=65$).

3.2.2.2. Late > Early Bilinguals, Past Tense Verb Generation: In contrast, Figure 3 displays the comparison of late > early bilinguals for all verbs, which revealed large regions of activation in the left middle frontal gyrus (dorsal lateral pre-frontal cortex: DLPFC), left angular gyrus extending into left inferior parietal lobule, right superior frontal gyrus (DLPFC), and left hippocampus. Smaller areas of activity were noted in the left precuneus, left cuneus, right precuneus, left superior parietal lobule, right middle frontal gyrus, left superior temporal gyrus, and right superior medial gyrus. When run as a multiple regression analysis, again controlling for proficiency metrics and participant gender, later L2 AoA correlated with a small region of activation in the left precuneus (27 voxels, Z-value = 3.43, peak of activity: $x=-9$, $y=-64$, $z=25$), which corresponds to the precuneus activation noted above in the cross-group comparison.

3.2.3. Verb Regularity Analyses—Although not the main thrust of this study, a considerable amount of research has investigated the difference between regular and irregular verbs. The main effect of verb regularity (i.e., both irregular verbs > regular verbs, and the opposite contrast, regular verbs > irregular verbs, collapsing across L2 AoA) revealed no statistically significant regions of activity at $P<.001$ uncorrected. An analysis of verb regularity by L2 AoA reveals very similar findings to those of all verbs taken together. More specifically, a comparison of early bilinguals > late bilinguals for irregular verbs revealed activations in left hemisphere insula, STG, pre-central gyrus, superior occipital gyrus, and post-central gyrus. For early bilinguals > late bilinguals using only regular verb stimuli, areas of activation were noted in the left hemisphere putamen extending into the thalamus, insula, pre-central gyrus, STG, and right middle temporal gyrus. For late > early bilinguals, the comparison of irregular verbs revealed activations in the right middle frontal gyrus, left hippocampus, and left angular gyrus extending into inferior parietal lobule. Regular verb generation for late > early bilinguals revealed areas of activity in the right superior frontal gyrus and angular gyrus, and left hippocampus and cuneus. No statistically significant interaction effects between L2 AoA and verb regularity were noted. Please see Table 4 for a summary of these results.

4. Discussion

4.1. Overview

The current study supports the predictions and our hypotheses regarding the influence of L2 AoA and the S/E model of language development. Early bilinguals preferentially recruited sensorimotor and motor control brain regions during production of the past tense in L2, whereas late bilinguals, to a greater degree, relied on executive processing regions when performing the same task. Taken together, these results suggest that both early and late learners use different neural routes and differing control mechanisms in order to generate the past tense in their second language, English.

4.2. Past Tense Generation

Although not the central goal of the present study, these results shed light on the nature of production of past tense generation in general. For our group of bilingual participants, past tense generation of English language verbs activated a diffuse language network including bilateral post-central gyrus, bilateral supplementary motor area, left precentral gyrus, right Rolandic operculum, and right temporal pole. Similar to other investigations of past-tense generation in monolinguals (Desai et al., 2006; Dhond et al., 2003), this pattern of activity likely represents the contributions of the brain's syntactic processing system, within the

context of a diffuse motor articulatory and language network. Together, these results indicate that the bilingual participants to a greater degree utilized brain regions thought to be involved in motor processing, control and planning strategies to perform this task. Furthermore, with a reduced statistical threshold, the syntactic processing regions (left hemisphere IFG) that are utilized by monolinguals are also similarly recruited by both bilingual groups when performing past tense generation (Desai et al., 2006; Dhond et al., 2003).

4.3. The L2 AoA Effect

Consistent with the view of the S/E model, when producing the past tense forms of verbs, early bilinguals preferentially recruited sensorimotor and motor control brain regions, while late bilinguals performing the same task preferentially relied on executive cognitive control regions. This notion is supported by the single group t-test results, as the early bilingual group recruits cortical and subcortical sensory and motor regions. The late bilingual group also recruited sensory regions, but additionally utilized executive control regions such as the inferior parietal lobule and DLPFC. In the direct comparisons, early versus late bilinguals revealed a strongly left lateralized pattern of activation for many structures whose activity has been implicated in sensorimotor language processing as well as the motor and language selection aspects of cognitive control (Abutalebi, 2008; Abutalebi & Green, 2007, 2008; Friederici, 2006). These regions included the left hemisphere insula / frontal lobe regions, putamen and other subcortical structures, supplementary motor area, and superior temporal gyrus. When compared to early bilinguals, late bilinguals utilized executive cognitive processing and control regions including the bilateral superior / middle frontal gyri, left angular gyrus and the left hemisphere hippocampus. Bilateral middle frontal gyrus activity has been implicated in various types of working memory (McMillan, Laird, Witt, & Meyerand, 2007) and memory retrieval processes (Hall, Gjedde, & Kupers, 2008). The hippocampus has been strongly implicated in both memory storage and retrieval processes (Scoville & Milner, 1957). The current results are somewhat consistent with the D/P model of bilingualism (Ullman, 2001a). Specifically, our results demonstrate more basal ganglia activation (procedural memory circuits) for early bilinguals, whereas late bilinguals utilize cognitive (declarative) memory circuits to a greater degree. However, our results did not demonstrate the dissociation between regular and irregular verbs that would be predicted by the D/P model.

These findings provide further support for the notion that early bilinguals experience a significant degree of neural “competition,” and must employ motor control mechanisms to a greater degree in order to perform the task. The current results provide an extension of the tenets of the cognitive control hypothesis that has been advanced by Abutalebi and Green, (2007, 2008). The cognitive control hypothesis suggests that early and late bilinguals utilize the same brain networks when performing tasks in the L2, but that the different areas of brain activation that have been observed between these groups in imaging investigations are the result of differential application of cognitive control. Abutalebi and Green have written that late bilinguals must employ a greater amount of cognitive control than early bilinguals to resolve lexical competition, and recruit brain regions such as dorsolateral prefrontal cortex, inferior parietal cortex, anterior cingulate cortex, and basal ganglia to do so. Indeed, consistent with some of this framework, we also see that early bilinguals activated the basal ganglia and inferior parietal lobule when performing this past tense generation task. Thus, the early bilinguals seem to utilize a sensorimotor and language selection control network when compared to late bilinguals. Interestingly, this difference remains despite the fact that the early bilingual group in this study does not differ from late bilinguals in language proficiency.

In contrast, late bilinguals engaged in the same task utilize relatively smaller areas of activity in a declarative memory network, which may represent increased reliance upon and resonance with an already entrenched linguistic system (the L1). However, different regions of the brain purported to be involved in executive cognitive control by Abutalebi, Green, and colleagues (e.g., bilateral DLPFC) were also shown in this contrast. Together, these results suggest that both the early and late bilingual groups utilize distinct neural networks to support L2 processing, with preferential reliance on differential cognitive control mechanisms. The late bilinguals utilized a network that relies on executive cognitive control to a greater extent.

The specific activations in the cross group comparisons provide further support for the sensorimotor hypothesis (Hernandez et al., 2005), and these findings are further supported by regression analyses that overlap with the cross group comparisons. The early bilinguals preferentially activated widespread motor control and motor articulatory regions, which is likely due to significant cognitive processing demands that are required to complete this task. Furthermore, our results suggest that the means by which early bilinguals generated the past tense forms of verbs required sensorimotor processes such as phonological retrieval and motor planning relative to late bilinguals. The early bilinguals recruited a large area in the left hemisphere insula, a region of the brain known for being involved in motor coordination (Ackermann & Riecker, 2004) and articulation (Dronkers, 1996; Bates, Wilson, Saygin, Dick, Sereno, Knight, et al., 2003) for linguistic activities. Furthermore, this group of participants preferentially recruited the left hemisphere putamen, which has been implicated in several types of motor coordination (Chang, Kenney, Loucks & Ludlow, 2009), including vocalization, due to its connections with the cortex and other basal ganglia regions (Jurgens, 2002; Booth, Wood, Lu, Houk, & Bitan, 2007), as well as motor control (Abutalebi & Green, 2007). Along these lines, activity of the putamen has been noted by other studies of bilingual language for L2 > L1 (Wartenburger et al., 2003), which may indicate the importance of employing motoric control mechanisms suggested by Abutalebi and Green. Further, putamen activity has been noted in Chinese-English bilinguals during a lexical decision task for verbs versus nouns (Chan, Luke, Li, Yip, Li, Weekes, & Tan, 2008). Moreover, the early bilingual group recruited the left SMA, a region thought to be involved in initiation and planning of motor sequences (Nachev, Kennard & Husain, 2008), as well as initiation of speech (Alario, Chainay, Lehericy & Cohen, 2010). Increased activity of the SMA has also been reported for word production in an L2 > L1 (Liu, Hu, Guo & Peng, 2010).

The sensorimotor aspects of this pattern of activation for early bilinguals seem to be well established, and it is the superior temporal gyrus activity that provides evidence for a different lexical retrieval route that is preferentially employed relative to late bilinguals. Left hemisphere superior temporal gyrus regions have been activated by lexical retrieval for less frequent words (Graves, Grabowski, Mehta, & Gordon, 2007) and for retrieval of lexical phonology (Damasio, Tranel, Grabowski, Adolphs & Damasio, 2004; Graves, Grabowski, Mehta & Gupta, 2008). Further, the activity of the left hemisphere superior temporal gyrus has been implicated in a number of sensory and linguistic processes including phonemic analysis (Liebenthal, Binder, Spitzer, Possing, & Medler, 2005). Taken together, the left hemisphere STG activity found in this contrast is likely due to phonological lexical retrieval strategies employed by this group of early bilinguals.

In contrast, later learners are able to preferentially utilize a direct access / declarative memory strategy based executive control regions for past tense verb generation. That late learners activated a network of brain structures, such as the hippocampus, left hemisphere angular gyrus and the bilateral superior/middle frontal gyrus, indicates that this group was able to rely on executive cognitive control and explicit declarative verbal memory retrieval

as well as recruiting online working memory and orthographic transformation strategies to generate the past tense forms of verbs. The hippocampus' role in lexical retrieval has been well established (Heckers, Weiss, Alpert, & Schacter, 2002). Others have ascribed left hippocampal activation to phonological loop rehearsal strategies (Balaguer, Rodriguez-Fornells, Rotte, Bahlmann, Heinze & Munte, 2006) and relational binding (Opitz & Friederici, 2003; Rudner, Fransson, Ingvar, Nyberg & Ronnberg, 2007). This finding of hippocampal activity bears some resemblance to the predictions of the declarative / procedural model, although Ullman (2001a, 2001b, 2004) and others (Takashima, Petersson, Rutter, Tendolkar, Jensen, Zwartz et al., 2006) would likely argue that L2 proficient late bilinguals would instead rely upon lateral temporal and temporoparietal or frontal regions for lexical retrieval. Anatomically, very similar posterior hippocampal activations have been noted for retrieval of words in the L2 (Jeong, Sugiura, Sassa, Wakusawa, Horie, Sato & Kawashima, 2010), and for processing of verbs (Kemmer, Gonzalez Castillo, Talavage, Patterson, & Wiley, 2008). An alternative explanation for this hippocampal activation is that the late bilinguals preferentially rely upon bound associations (such as an image), whereas early bilinguals generate the past tense form of the verb more automatically without making such an association.

A number of investigations have provided support for the involvement of bilateral middle/superior frontal gyrus for processes such as working memory and memory retrieval processes, as well as for cognitive control. Multiple investigations (Cornette, Dupont, Salmon, and Orban, 2001; Hayama & Rugg, 2009) have described the recruitment of the right hemisphere middle frontal gyrus for participants while engaged in the process of updating working memory. Similar support for the involvement of this structure in working memory processes is derived from studies that have reported activity in middle frontal gyrus for participants during an N-back task (McMillan et al., 2007; Casey et al., 1998). Alternatively, a number of investigators have reported activity in the superior/middle frontal gyrus for memory recall of voluntary versus involuntary material (Hall et al., 2008), and maintenance of episodic memory retrieval mode (Lepage, Ghaffar, Nyberg & Tulving, 2000). In the context of this study, then, the relatively greater recruitment of middle frontal gyrus and inferior parietal lobule in late bilinguals is likely due to executive cognitive control and working memory processes that are required to attend to and recall verb forms during the experimental task.

In addition to the working memory aspects of cognitive control (Abutalebi and Green, 2007), the angular gyrus and surrounding regions have classically been thought to be involved in cognitive tasks such as word reading and transforming orthographic to phonological information (Carreiras, Seghier, Baquero, Estevez, Lozano, Devlin & Price, 2009; Cornelissen, Kringelbach, Ellis, Whitney, Holliday, & Hansen, 2009) and silent reading (Gates & Yoon, 2005). Alternative views of the activity of the angular gyrus include accessing the semantic system (Price, 2000) and transferring orthography to semantics (Graves, Desai, Humphries, Seidenberg & Binder, 2010) and a component of auditory working memory (Dronkers, Wilkins, Van Valin Jr., Redfern, & Jaeger, 2004). That the late bilinguals recruited the left angular gyrus region may be related to preferential reliance upon other cognitive processes (e.g., reading) that were developing at the same time as these individuals were learning the L2.

4.4. Conclusion

In summary, an overall comparison of our data indicate that production of past tense for early bilinguals is preferentially a function of a diffuse sensorimotor control and motor planning network. Late bilinguals performing the same task appear to rely to a greater degree on a direct lexical memory access strategy with reliance on executive cognitive control and working memory circuits. In other words, both early and late bilinguals recruited

brain regions hypothesized to play a role in control, but different control mechanisms (i.e., motoric vs. executive) are preferentially employed based on L2 AoA with regard to the neural systems and cognitive capacities that are being utilized when the L2 is acquired. Specifically, early bilinguals recruited relatively large areas of activity in sensorimotor brain regions that are commonly associated with a complex language and motor control network. This preferential recruitment likely reflects the greater demands related to control that are required in performing the task. Congruent with the S/E model, this activation pattern may be the result of competition between the neural networks that support the participant's L1 and L2. These data also suggest that relative to early bilinguals, late bilinguals are able to generate the past tense forms of verbs while employing a strategy that requires a different, more executive, mechanism of control. Support for these findings can be derived from our data in that generation of the past tense forms of verbs in late bilinguals revealed small activations in the bilateral middle/superior frontal gyri, left hemisphere hippocampus and left angular gyrus/inferior parietal lobule region, when compared to early bilinguals.

The results of the present study also help to qualify in important ways the influence of developmental variables on the nature of bilingual brain activity during past tense generation tasks. The current results are consistent with the S/E model in that early bilinguals experienced a greater degree of cognitive demand to perform the task. This demand was demonstrated in the greater extent of brain activation in regions of the brain thought to be involved in the motor and language selection aspects of cognitive control. This finding may be the result of competition between the participant's L1 and L2 due to the near simultaneous acquisition of two languages prior to the entrenchment of a neurolinguistic architecture. Notably, this activity was most evident in regions of the brain thought to be involved in the motor aspects of control and sensorimotor processing.

The presence of increased activity in the bilateral superior/middle frontal gyri, hippocampus, and left inferior parietal lobule serve as an extension of the predictions made by the cognitive control model of Abutalebi and Green (2007, 2008). However, regions of the brain that are thought to be involved in the employment of different aspects of cognitive control were utilized, although in a different manner for early bilinguals. Hence, our data suggests that different retrieval and control mechanisms, motoric vs. executive, are being used by both early and late bilinguals, respectively. Taken together, the current results support the notion that bilingual language learning and production is a function of sensorimotor and cognitive control processes, although the type of control depends on the bilingual's AoA. Specifically, early bilinguals preferentially rely on motor aspects of control, while late bilinguals recruit brain regions involved in executive and working memory aspects of cognitive control to a greater degree. Future studies are needed to further investigate similar populations, including regression based analyses, in order to further our understanding of AoA on the nature of brain activity in L2 learners.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Highlights

- fMRI study to investigate bilingual language learning using past tense generation.
- Early bilinguals recruited motoric control and sensorimotor brain regions.
- Late bilinguals relied on executive cognitive control and direct lexical access.
- Data support an extension of cognitive control theory and the sensorimotor hypothesis.

Figure 1.

a) 3D rendered brain activation patterns for past tense generation relative to rest for all participants, combined. Activations are significant at $p < .001$ uncorrected, 10 voxel minimum threshold. Activations from 8 mm below the surface have been projected to the cortex. Areas of activity noted in bilateral motor articulatory regions. Please see Table 2 for a complete listing of activations. b) 3D rendered brain activations for the early bilingual group using the same parameters. c) 3D rendered brain activations for the late bilingual group using the same parameters.

Figure 2. Cross group comparison. Verb Generation, Early Bilinguals > Late Bilinguals. Activations are significant at $p < .001$ uncorrected. Areas of activity noted in bilateral sensory and motor regions. Please see Table 3 for a complete listing of activations.

Figure 3. Cross group comparison. Verb Generation, Late Bilinguals > Early Bilinguals. Activations are significant at $p < .001$ uncorrected. Areas of activity noted in regions involved in direct executive cognitive control, and lexical retrieval. Please see Table 3 for a complete listing of activations.

Table 1

Demographic and behavioral data for early and late bilinguals.

Behavioral Performance					
		Early Bilinguals Late Bilinguals Cross group comp.Group Total/Avg			
Demographic Information	n	11 (11 females)	11 (4 females)		22 (15 female)
	age	21.5 (1.7)	24.9 (4.1)	p=.02	23.18 (3.6)
Pre-Scan Proficiency Measures	Boston Naming Test	44.1 (5.8)	47.4 (6.8)	p=.26	45.7 (6.5)
	WLPB (Picture Vocabulary)	36.8 (4.1)	39.2 (4.2)	p=.21	38.0 (4.3)
	WLPB (Comprehension)	36.7 (3.0)	39.1 (4.6)	p=.18	37.9 (4.1)
	WLPB (Listening Comp.)	29.2 (2.9)	30.7 (3.6)	p=.31	30.0 (3.4)
Post-Scan Performance	Verb Generation % Errors	4.1	9.1	t=2.58, p=.02	

Table 2

Activation regions by condition: group analyses

Contrast	Voxels	Approx BA	Side	Region	x	y	z	Z-Value
All participants <i>Verb_Gen > Rest</i>	402	3/4	L	Precentral Gyrus	-36	-20	51	5.60
		3	L	Inferior Parietal Lobule	-38	-30	37	4.63
		3	L	Postcentral Gyrus	-46	-24	37	4.62
		3	L	Postcentral Gyrus	-44	-26	39	
		3	L	Postcentral Gyrus	-40	-28	41	
	48	6	R	Supplementary Motor Area	10	-8	67	3.35
		6	R	Supplementary Motor Area	4	-14	69	3.32
		6	R	Supplementary Motor Area	12	-6	65	
	40		R	Rolandic Operculum	50	-2	11	4.13
	31	24	R	Middle Cingulate	12	2	47	3.62
	30	6	L	Supplementary Motor Area	-10	-8	59	3.35
		6	L	Supplementary Motor Area	-8	-6	55	
	22	3	R	Postcentral Gyrus	64	-12	25	3.47
			R	Postcentral Gyrus	64	-16	19	
	18		L	Subcortical White Matter	-12	0	43	3.54
	13	6	R	Subcortical White Matter	26	-18	51	3.25
	13		L	Subcortical White Matter	-24	-10	49	3.25
	10		R	Temporal Pole	52	2	-1	3.50
Early bilinguals <i>Verb_Gen > Rest</i>	158	3/4/6	L	Postcentral Gyrus	-44	-11	40	3.63
	155		L	Insula	-43	-1	6	3.97
	100	6	L	Supplementary Motor Area	-4	-6	63	3.55
	80		L	Pallidum	-21	-4	10	3.96
	42	44	L	Inferior Frontal Gyrus	-48	0	20	3.58
	33	3/4	R	Postcentral Gyrus	63	-15	23	3.97
	29	47	L	Inferior Frontal Gyrus	-37	22	-5	4.30
	26	3/4	R	Postcentral Gyrus	48	-18	44	3.81
	26	3	L	Inferior Parietal Lobule	-39	-26	42	3.63

Contrast	Voxels	Approx BA	Side	Region	x	y	z	Z-Value
Late bilinguals <i>Verb_Gen > Rest</i>	20	19	L	Superior Occipital Gyrus	-23	-71	41	4.25
	216	2/3/4	L	Postcentral gyrus	-33	-30	48	4.48
	41		L	Middle Cingulate Cortex	-13	-3	45	4.70
	39		L	Hippocampus	-29	-45	4	4.16
	32	3	R	Postcentral Gyrus	42	-29	37	3.86
	23	2	R	Inferior Parietal Lobule	35	-44	54	4.16
	15		L	Medial Frontal Gyrus	-17	-16	50	3.37
	11	9	L	Middle Frontal Gyrus	-26	26	32	3.64

Table 3

Activation regions by condition: main effect L2 AoA analyses.

Contrast	Voxels	Approx BA	Side	Region	x	y	z	Z-Value
<i>Verb_Gen: Early>Late</i>	1113		L	Insula	-44	2	7	5.14
		4	L	Precentral Gyrus	-40	-8	35	4.75
		3/1/2	L	Postcentral Gyrus	-58	-4	19	4.55
	406	22	L	Superior Temporal Gyrus	-58	-50	23	4.89
		40	L	Supramarginal Gyrus	-60	-38	29	4.12
		21	L	Middle Temporal Gyrus	-48	-60	15	4.06
	381		L	Putamen	-22	-6	11	4.93
			L	Thalamus	-12	-28	11	3.71
	316	6	L	Supplementary Motor Area	-4	6	65	4.05
	127	21	R	Middle Temporal Gyrus	52	-48	13	4.21
		22	R	Superior Temporal Gyrus	54	-50	21	3.60
	107	19	L	Superior Occipital Gyrus	-22	-70	39	5.19
	24	4	R	Precentral Gyrus	46	-12	55	3.41
	21	18	R	Calcarine Gyrus	6	-78	19	3.30
	16	17	R	Lingual Gyrus	24	-54	5	3.43
	15		R	Middle Cingulate	10	4	39	3.52
	14	7	L	Inferior Parietal Lobule	-30	-52	49	3.55
	14		R	Supercortical Gray Matter	2	-36	-3	3.39
	11		R	Thalamus	10	-16	9	3.56
<i>Verb_Gen: Late>Early</i>	388	8/9/46	L	Middle Frontal Gyrus	-34	12	59	4.59
			L	Superior Medial Gyrus	-4	38	55	4.29
	341	39	L	Angular Gyrus	-48	-66	49	4.16
			L	Inferior Parietal Lobule	-36	-76	47	4.08
	273	8/9/46	R	Superior Frontal Gyrus	24	36	47	5.08
	235		L	Hippocampus	-26	-44	7	5.22
	97		L	Precuneus	-12	-56	39	3.80
	48		L	Cuneus	-6	-84	45	4.14
	36		R	Precuneus	8	-60	25	3.73
	33	7	L	Superior Parietal Lobule	-30	-52	65	3.90

Contrast	Voxels	Approx BA	Side	Region	x	y	z	Z-Value
	27	8/9	R	Middle Frontal Gyrus	50	10	47	3.75
	19	22	L	Superior Temporal Gyrus	-56	-24	11	3.40
	16		R	Superior Medial Gyrus	2	44	47	3.79
	15		L	Subcortical WM	-28	12	29	3.84

Table 4

Activation areas by condition: L2 AoA and verb regularity.

Contrast	Voxels	Approx BA	Side	Region	x	y	z	Z-Value
<i>Irregular: Early>Late</i>	69		L	Insula	-44	2	7	3.81
	65	22	L	Superior Temporal Gyrus	-58	-52	21	4.19
	42	4	L	Precentral Gyrus	-40	-8	37	3.52
	25	19	L	Superior Occipital Gyrus	-22	-70	39	4.10
	10	3	L	Postcentral Gyrus	-58	-4	19	3.48
<i>Regular: Early>Late</i>	169		L	Putamen	-22	-6	11	4.40
			L	Thalamus	-16	-16	13	3.37
	137		L	Insula	-33	2	7	4.03
	50	4	L	Precentral Gyrus	-40	-8	35	3.69
	16	22	L	Superior Temporal Gyrus	-58	-40	27	3.65
<i>Irregular: Late>Early</i>	11	22	L	Superior Temporal Gyrus	-56	-48	25	3.40
	10	21	R	Middle Temporal Gyrus	52	-46	11	3.29
	38	8/9	R	Middle Frontal Gyrus	26	36	45	3.71
	33		L	Hippocampus	-26	-44	7	4.16
	30	39	L	Angular Gyrus	-54	-68	37	3.52
Regular: Late>Early			L	Inferior Parietal Lobule	-50	-64	51	3.16
	85	8/9	R	Superior Frontal Gyrus	24	36	49	4.11
	19	39	R	Angular Gyrus	34	-74	49	3.48
	19		L	Hippocampus	-24	-44	7	3.83
	13		L	Cuneus	-6	-84	45	3.68