

# Bilingual and Monolingual Brains Compared: A Functional Magnetic Resonance Imaging Investigation of Syntactic Processing and a Possible “Neural Signature” of Bilingualism

Ioulia Kovelman<sup>1,2</sup>, Stephanie A. Baker<sup>1</sup>, and Laura-Ann Petitto<sup>1,3</sup>

## Abstract

■ Does the brain of a bilingual process language differently from that of a monolingual? We compared how bilinguals and monolinguals recruit classic language brain areas in response to a language task and asked whether there is a “neural signature” of bilingualism. Highly proficient and early-exposed adult Spanish–English bilinguals and English monolinguals participated. During functional magnetic resonance imaging (fMRI), participants completed a syntactic “sentence judgment task” [Caplan, D., Alpert, N., & Waters, G. Effects of syntactic structure and propositional number on patterns of regional cerebral blood flow. *Journal of Cognitive Neuroscience*, 10, 541–552, 1998]. The sentences exploited differences between Spanish and English linguistic properties, allowing us to explore similarities and differences in behavioral and neural responses between bilinguals and monolinguals, and between a bilingual’s two languages. If bilinguals’ neural processing differs across their two languages, then differential behavioral and neural patterns should be observed in Spanish and English. Results show that behaviorally, in English, bilinguals and monolinguals had the same speed and accuracy, yet, as predicted from the Spanish–

English structural differences, bilinguals had a different pattern of performance in Spanish. fMRI analyses revealed that both monolinguals (in one language) and bilinguals (in each language) showed predicted increases in activation in classic language areas (e.g., left inferior frontal cortex, LIFC), with any neural differences between the bilingual’s two languages being principled and predictable based on the morphosyntactic differences between Spanish and English. However, an important difference was that bilinguals had a significantly greater increase in the blood oxygenation level-dependent signal in the LIFC (BA 45) when processing English than the English monolinguals. The results provide insight into the decades-old question about the degree of separation of bilinguals’ dual-language representation. The differential activation for bilinguals and monolinguals opens the question as to whether there may possibly be a “neural signature” of bilingualism. Differential activation may further provide a fascinating window into the language processing potential not recruited in monolingual brains and reveal the biological extent of the neural architecture underlying all human language. ■

## INTRODUCTION

Questions about whether a bilingual can ever fully acquire two language systems, each with monolingual proficiency, and debate over whether knowing two languages helps or hinders the processing of either language, have led to one of the most hotly pursued research questions among contemporary language scientists: Does a bilingual brain, even when a bilingual is using only one language, process linguistic information in the same manner as a monolingual brain? Can early dual-language exposure modify the neural tissue classically observed to underlie human language processing in a way that renders language processing in bilinguals fundamentally different from that of monolinguals? To a certain extent, this neural organization is influenced by

environmental experiences and, therefore, many early childhood experiences, such as sensory deprivation, musical training, learning to read, and delays in language exposure, have the potential to yield a life-long impact on behavior as well as on brain organization (Newman, Bavelier, Corina, Jezzard, & Neville, 2002; Neville & Bavelier, 2001; Ohnishi et al., 2001; Petersson, Reis, Askelof, Castro-Caldas, & Ingvar, 2000). Might early exposure to two languages yield changes in the pattern of neural activity within classic language brain areas in bilinguals (hence, a “neural signature”)?

Despite this focus, most previous research has not involved direct study of language processing in the brains of bilinguals as compared to monolinguals. Instead, the lion’s share of research has focused either on language processing in the brains of bilinguals who had early versus late exposure to their two languages (Klein, Watkins, Zatorre, & Milner, 2006; Frenck-Mestre, Anton, Roth, Vaid, & Viallet, 2005; Mahendra, Plante, Magloire,

<sup>1</sup>Dartmouth College, <sup>2</sup>Massachusetts Institute of Technology, <sup>3</sup>University of Toronto Scarborough

Milman, & Trouard, 2003; Marian, Spivey, & Hirsch, 2003; Perani et al., 2003; Friederici, Steinhauer, & Pfiefer, 2002; Weber-Fox & Neville, 1996, 2001; Dehaene et al., 1997; Kim, Relkin, Lee, & Hirsch, 1997), language processing in bilinguals who have *high* proficiency in each of their two languages versus those with *low* proficiency in one of the two (Chee, Soon, Lee, & Pallier, 2004; De Bleser et al., 2003; Perani et al., 2003; Wartenburger et al., 2003), or *language switching* in bilinguals (Rodriguez-Fornells et al., 2005; Rodriguez-Fornells, Rotte, Heinze, Noesselt, & Munte, 2002; Grosjean, 2001; Hernandez, Martinez, & Kohnert, 2000; Price, Green, & von Studnitz, 1999; Paradis, 1997). Here we directly compare how the brains of bilinguals and monolinguals process linguistic information, using a combination of behavioral and functional magnetic resonance imaging (fMRI) techniques, to understand whether being bilingual, per se, modifies the classic language-dedicated neural sites and pathways underlying human language processing. Is there a “neural signature” of being bilingual—for example, does early exposure to two languages modify how bilinguals recruit classic language brain tissue as compared to monolinguals? If so, is there a behavioral consequence—an improvement or deficit in language processing in one or both languages?

One important area of lively research in the psycholinguistic literature has focused on what bilinguals *know* about their languages as well as how bilinguals organize the knowledge of their two linguistic systems. Do bilinguals have one general (or “fused”) language representational system or two distinct (or “differentiated”) language representational systems (that is, a unique representational system for each language)? (For a discussion of “fused” vs. two “differentiated” linguistic representational systems in bilinguals, see, e.g., Fernandez, 2002; Grosjean, 2001; Meisel, 2001; Mueller & Hulk, 2001; Petitto et al., 2001; Lanza, 2000; De Houwer, 1999; Paradis, 1997; Hernandez, Bates, & Avila, 1994; Genesee, 1989). Similarly, an important question in the cognitive neuroscience literature has been whether bilingual language processing draws upon one common neural system or two distinct neural systems (one for each language)?

Decades of illuminating behavioral psycholinguistic research with adults have advanced our understanding of how bilinguals process items in their dual lexicons as compared to monolinguals (e.g., see Gollan & Kroll, 2001; Van Hell & De Groot, 1998a, 1998b; De Groot, 1992). Researchers have provided strong evidence that bilinguals do differ fundamentally from monolinguals, especially regarding the existence of *differentiated* dual lexicons, the existence and nature of the connections between their differentiated dual lexical representations, as well as in the control needed to use one lexical item versus the other. Bilinguals have been observed to translate concrete words faster than abstract words (Van Hell & De Groot, 1998b) and researchers have also shown that bilinguals can be semantically primed in one

language to produce a word in the other language (Kroll & Sunderman, 2003; Dijkstra & Van Heuven, 2002), suggesting that although lexico-semantic representation across a bilingual’s two lexicons can show facilitation, they involve distinct (not shared) lexical stores. Others have suggested the existence of one combined lexico-semantic store that is similar to monolinguals (Ameel, Storms, Malt, & Sloman, 2005; Kroll & Sunderman, 2003; Dijkstra & Van Heuven, 2002; Green, 1998; Kroll & Stewart, 1994). Although this rich discussion of lexical and semantic representation in bilinguals and monolinguals continues, comparatively little has been offered about how bilinguals versus monolinguals process other important aspects of language structure, especially syntax and morphology, which are crucial in the processing of full sentences in natural language. In this article, we focus on the syntactic and morphological levels of language structure in the brains of bilinguals versus monolinguals.

Presently, most developmental psycholinguistic research with young children supports the view that young bilinguals are developing two differentiated linguistic systems from early in infancy (Petitto & Kovelman, 2003; Holowka, Brosseau-Lapr , & Petitto, 2002; Petitto et al., 2001; De Houwer, 1999; Pearson, Fernandez, & Oller, 1993; Genesee, 1989). This understanding stands in contrast to several decades of earlier claims that young bilinguals’ two languages are “fused” into one general language system during early life and does not become differentiated into two linguistic systems until ages 4 to 5 years (e.g., Vihman, 1985; Volterra & Taeschner, 1978).

Although contemporary developmental findings are consistent with the presence of differentiated (and distinct) language representations in young bilinguals, this is not to suggest that a bilingual’s two languages do not interact. Evidence of cross-linguistic influence in young children has suggested that at least some aspects of one of a bilingual child’s languages impact some aspects of the other language (Paradis & Navarro, 2003; Nicoladis, 2002; Doepke, 2000; Schellert, 2000). Cross-linguistic interference in young bilinguals has been found in most key aspects of language competence, including word meaning, (semantics; Kohnert, Bates, & Hernandez, 1999), word formation (morphology; Nicoladis, 2002), sound perception (phonology; Fennell, Byers-Heinlein, & Werker, 2006), and sentence structure (syntax; Paradis & Navarro, 2003; Mueller & Hulk, 2001).

Like children, bilingual adults also show evidence of cross-linguistic influence. This is particularly prevalent in late and low-proficiency bilinguals, when second-language processing is heavily influenced by first/dominant language (Liu, Bates, & Li, 1992). Hernandez et al. (1994) examined morphosyntactic strategies that govern bilinguals’ sentence processing from within a “Computational Model Framework” (Bates & MacWhinney, 1989), which suggests that language comprehension is

a process during which a set of linguistic forms competes to yield a particular interpretation. Hernandez et al. suggested that bilingual adults predominantly use an “amalgamation” strategy of combining morphosyntactic forms taken from the two languages, rather than a “differentiated” strategy of using language-specific forms for each of their languages. Another suggestion is that bilinguals might be capable of processing two languages “independently, yet in parallel” (Grosjean, 2001), making it even more challenging for researchers to determine which instances of a bilingual’s language production are examples of “amalgamation,” “dominance,” or “parallel” processing of two “differentiated” linguistic systems. Thus, lively debate continues as to whether adult bilinguals fully differentiate their linguistic systems and can ever achieve monolingual-like language competence in two systems.

Despite great interest in how the bilingual brain houses two languages and the extent to which bilinguals’ two linguistic systems may be fused or differentiated in one brain, existing brain research is equivocal. Classic neuropsychological studies of bilingual aphasics have shown that individuals may selectively lose only one language and not the other, thereby supporting a language differentiation view (Paradis, 1977). Neuroimaging studies have focused on the *age* of first bilingual language exposure as well as the level of *language proficiency* in each of a bilingual’s two languages as windows into bilingual brain organization and processing. Regarding age, early bilingual language exposure has been found to result in bilinguals using the same neural tissue for processing *both* of their languages as has been classically observed in monolinguals. It has been suggested that late bilingual exposure results in a different neural profile, whereby there is greater frontal and bilateral recruitment of neural tissue for the *later* acquired language (Marian et al., 2003; Hahne & Friederici, 2001; Weber-Fox & Neville, 1999, 2001; Hernandez et al., 2000; Dehaene et al., 1997; Kim et al., 1997). Importantly, syntax, select aspects of morphology, and phonology are the levels of language organization that require language exposure during key maturational age periods in order to achieve full behavioral mastery and native-like language organization in the brain; for example, with phonology, witness that few succeed in overcoming their nonnative accents when learning a second language later in life (Weber-Fox & Neville, 1999, 2001; Flege, MacKay, & Meador, 1999; Johnson & Newport, 1989). On the other hand, new semantic information (e.g., learning new words) can be easily acquired throughout the lifespan, and semantic processing and its organization in the brain are comparatively less impacted by the age of first language exposure (Weber-Fox & Neville, 1999, 2001; Illes et al., 1999).

Language proficiency, in both early and late bilinguals, has also been found to impact bilingual language organization in the brain (Chee et al., 2004; Perani et al.,

2003; Wartenburger et al., 2003). For instance, using semantic and phonological language processing tasks, Chee et al. (2004) showed neural differences in bilingual brains depending on whether they had high versus low language proficiency in each language, independent of the age of acquisition. To reconcile the question of whether it is the age of exposure or proficiency that has more impact, Wartenburger et al. (2003) conducted a study showing that both age and proficiency influence the neural organization of two languages in one brain. Finally, a structural imaging study of gray matter density in high- and low-proficiency bilinguals versus monolinguals revealed the fascinating finding that bilinguals have an increase in gray matter volume in the left inferior parietal lobe as compared to monolinguals (Mechelli et al., 2004). The greatest increase in gray matter volume was in early high-proficiency bilinguals, and the lowest was in late low-proficiency bilinguals.

To the best of our knowledge, only a few neuroimaging studies exist that involve comparisons of how the brains of bilinguals versus monolinguals process linguistic information. Most of these investigations are indirect comparisons of neural activation in bilingual versus monolingual brains during language switching/differentiation tasks (Rodríguez-Fornells et al., 2002, 2005; Quaresima, Ferrari, van der Sluijs, Menssen, & Colier, 2002; Hernandez et al., 2000; Price et al., 1999). These imaging studies have yielded the important finding that specific brain areas are involved in bilingual switching: dorsolateral prefrontal cortex, inferior frontal cortex, anterior cingulate, and supramarginal gyrus. Overall, bilingual switching studies suggest that at least in one language context—one that specifically involves the rapid switching from one language to another—we should observe that bilinguals’ brains function differently from those of monolinguals. However, what still needs further study is whether activation in these brain areas is unique to the bilingual brain during language switching or is shared with other cognitive switching tasks (and therefore, would be found in monolinguals as well).

The scarcity of direct comparisons of bilingual versus monolingual brains during language processing tasks—and the need for tasks involving more complete levels of language competence (e.g., morphological and syntactic)—leaves unanswered questions about the similarities and differences between monolingual and bilingual brains. First, it is still equivocal as to whether bilinguals recruit the same classic language areas in the same manner, for the same functions of language processing, and with the same location and extent as monolinguals—including the superior temporal gyrus (STG; BA 42/22), which is known to be important in phonological processing (e.g., Zatorre & Belin, 2001; Petitto et al., 2000), and the left inferior frontal cortex (LIFC); the LIFC is a large left inferior frontal area that has been typically observed to participate in all

aspects of language processing, including morphosyntax, semantics, and phonology. It incorporates pars triangularis and pars opercularis (including the classic Broca's area; Price, 2000; Foundas, Eure, Luevano, & Weinberger, 1998) and spans Brodmann's areas 47, 45, 44, and 6 (Hagoort, 2005).

Second, the anatomical studies noted above suggest that there are structural changes in a person's brain as a result of extensive bilingual exposure, including enlargement of brain areas such as the inferior parietal cortex (Mechelli et al., 2004). Thus, another important question is whether such purported structural changes in the brains of bilinguals also result in differences between bilingual versus monolingual language processing. Only a direct comparison between bilinguals and monolinguals, using neuroimaging and behavioral paradigms, would ideally address these issues.

In the present study, we conduct direct comparisons of the brains of early-exposed (birth to before age 5) and highly proficient Spanish–English bilinguals and English monolinguals using a “sentence judgment task” that participants performed while undergoing fMRI. Both bilingual and monolingual language groups judged an identical set of sentences in English, and bilinguals also judged a set of sentences in Spanish. Requiring that our bilingual participants had to have early and maintained dual-language exposure was motivated by behavioral evidence suggesting that language competence in bilinguals with first bilingual exposure before age 5 is commonly indistinguishable from that of monolingual native speakers (Weber-Fox & Neville, 1999, 2001; Johnson & Newport, 1989) and that their neural organization tends to be similar across the two languages and similar to that of monolinguals (Kim et al., 1997). Only early-exposed bilinguals constitute the most apt point of comparison to monolinguals (similarly exposed to language from early life), hence, permitting the ideal basis for comparing language representation in the bilingual versus monolingual brain.

Another intentional design feature was our study of Spanish–English bilinguals while in an *English-only* processing mode and, crucially, while in a *Spanish-only* processing mode, with each mode being compared to matched *English* monolinguals (for discussion of bilingual modes of language use, see Grosjean, 2001). In order to create “monolingual” Spanish and “monolingual” English modes for bilinguals, each language was presented separately and in succession in a block design with predictable language order (introduced during the training phase) and between block warnings about which language was to come so as to avoid any possibility of initiating a language switching mode. As this research was not conducted in an officially monolingual Spanish-speaking country, a monolingual Spanish-speaking comparison group was not available to us. Hence, we chose an experimental design that would, nonetheless, provide new and valid findings concerning neural organization in lan-

guage contexts more typical for a bilingual during his or her day (i.e., while processing in one language mode versus in the other), and which are thus most generalizable to everyday demands of dual-language processing in bilinguals.

Sentence judgment tasks have been a standard paradigm for assessing grammatical knowledge in studies of monolingual and bilingual language processing (Fernandez, 2002; Bates, Devescovi, & D'Amico, 1999; Blackwell, Bates, & Fisher, 1996; Hernandez et al., 1994; Liu et al., 1992). Here we used a sentence judgment task with relative-clause sentences selected from a set previously used by Caplan (2001), Caplan, Alpert, and Waters (1998), and Stromswold, Caplan, Alpert, and Rauch (1996). The specific sentences chosen possessed two types of morphological and syntactic (“morphosyntactic”) complexity that have been observed in the world's languages: the more prevalent or “unmarked” object–subject sentence type (OS, as in “The child spilled the juice that stained the rug”; “El niño derramó el jugo que manchó la alfombra”), and the less prevalent or “marked” subject–object sentence type (SO, as in “The juice that the child spilled stained the rug”; “El jugo que el niño derramó manchó la alfombra”).

The two different relative-clause sentence types above (SO and OS) exploit the differences between particular types of linguistic constructions in a language (as well as their typical frequency in a particular language), and thus, lay bare the nature of an individual's processing in that language. English (which belongs to the “analytic,” syntax-based, class of world languages) has comparatively minimal reliance on morphological markings, and instead, has a much heavier reliance on strict word order, and changes in word order, to signal changes in meaning. For example, in the following two English sentences “Mary killed John” and “John killed Mary,” the subject–object grammatical relations (or, who did what to whom) are conveyed merely by changing the ordering of the identical three words, rather than by adding subject–object markings on individual words in the sentence. Generally speaking, languages that rely most heavily on word order rely less heavily on morphological markings, and vice versa. As a case in point, Spanish has a rich reliance on morphological markings, and comparatively less reliance on strict word order. Consequentially, when reading a sentence, monolingual English speakers find word order information more salient than morphological information (this is not to say that English-speakers completely ignore morphological information), whereas Spanish readers pay greater attention to morphological cues than to syntactic cues (Fernandez, 2002; Hernandez et al., 1994; MacWhinney & Bates, 1989). We reasoned that it would be intriguing to use such differences in the reliance on word order versus morphology between English and Spanish (respectively) as a tool to reveal possible differences/similarities in the patterns of neural activity in the brains



of bilinguals depending upon the language that they were “in.” For example, if bilinguals have “differentiated” linguistic systems, then we would predict that the Spanish–English bilingual, in Spanish, would show less differences in brain activity between the two sentence types with varying word order (as word order is not as informative in Spanish) than in English (as word order is more informative in English).

We further selected the above sentences because neuroimaging and behavioral research over the past decade have yielded highly consistent results with English monolinguals (e.g., Caplan, Waters, & Alpert, 2003; Caplan, Alpert, Waters, & Olivieri, 2000; Caplan et al., 1998). To be sure, these sentences have revealed consistent behavioral and brain responses due specifically to changes in syntactic complexity that are not due to semantic or working memory components of the stimuli (Caplan, 2001; Caplan et al., 1998, 2000; Stromswold et al., 1996). Typically, English monolinguals show a *decrease* in speed and accuracy in their *behavioral* performance and an *increase* in the *neural* involvement of the LIFC (BA 44/45) during more complex (SO) versus less complex syntactic (OS) stimuli. Similar results have been consistently observed across a wide variety of populations, including individuals suffering from aphasia, young and healthy adults, as well as healthy aging adults (Caplan et al., 1998, 2003; Stromswold et al., 1996). There is also confidence that such findings are not a result of semantic rather than syntactic processing of these complex sentences (e.g., the debate about the existence of neural mechanisms that are differentially dedicated to processing of syntactic versus semantic information; e.g., Friederici, 2001; Dapretto & Bookheimer, 1999). First, although semantic processing is, of course, involved, it is held constant across SO/OS sentence types in these stimuli (Caplan et al., 1998). The results have also been replicated under multiple conditions, when semantic and working memory components have been varied along with the syntactic complexity of the sentences (e.g., Caplan et al., 2000; Caplan, Hildebrandt, & Makris, 1996).

Taken together, direct neuroimaging and behavioral comparisons of bilingual versus monolingual brains can provide new insights into the biological extent of the neural architecture underlying all human language and yield testable hypotheses about *how* bilinguals process two languages in one brain. If bilinguals have one “fused” linguistic system, then they should show a similar location and extent of the peak of BOLD activation and similar levels of BOLD signal intensity for both of their languages, irrespective of cross-linguistic differences in the sentence stimuli. This similarity in the location/extent and intensity of BOLD activation should be observed within the LIFC [which incorporates the classic Broca’s area (Hagoort, 2005) and which includes the pars opercularis and pars triangularis, BA 44/45 and BA 44/46]—neural tissue that has been shown to be

particularly sensitive to syntactic information (Caplan, 2001; Friederici, 2001; Ni et al., 2000; Chee et al., 1999; Dapretto & Bookheimer, 1999; Caplan et al., 1996). Behaviorally, it is predicted that there will be fundamental *similarities* in reaction time (RT) and accuracy irrespective of whether the bilingual is processing Spanish or English, although the role of sentence type is less clear (and depends, in this case, on whether the bilingual is more influenced by the nature of word order constraints in English or rich morphological markings in Spanish).

By contrast, if bilinguals have differentiated linguistic systems, then they should show differentiation in the recruitment of the classic language brain areas when processing each of their two languages. They should (i) show a different signal intensity of BOLD activation when in Spanish versus when in English, and during English stimuli presentation, the brains of bilinguals should (ii) show a neural activation pattern similar to that of English monolingual speakers when processing different sentence types in English (SO or OS). Behaviorally, bilinguals should demonstrate performance that is different across each of their two languages. Of greatest interest here, of course, would be the discovery of any neural differences (e.g., involving location and extent and/or signal intensity) observed when bilinguals are processing English versus when monolinguals are processing English. If bilinguals and monolinguals, in English, show significant differences in the patterning of neural activation in the LIFC and/or the superior temporal gyrus, this, indeed, will be suggestive of a possible “neural signature” of bilingualism.

## METHODS

### Participants

Eleven Spanish–English right-handed bilinguals (7 women and 4 men, mean age = 19 years, range = 18–22 years) and 10 English right-handed monolinguals (5 women and 5 men; mean age = 20 years, range = 18–26 years) participated in the study (see the summary of participant information in Table 1).

Most of the bilingual Spanish–English participants (8 out of 11) received their bilingual exposure from birth, with the remaining three receiving first bilingual exposure at the ages of 4–5 years (but not after age 5). All bilinguals were living and studying in the United States at the time of testing. All bilinguals learned to read in English at school, and in Spanish at home. Five of the bilingual participants received formal bilingual education during either elementary, middle, or high school, and all participants had at least one class of formal education in Spanish. The primary language of university instruction for all bilingual participants was English. All bilingual participants judged themselves to be bilingual and bicultural, and considered themselves to be equally fluent

**Table 1.** Participant Information

Participants	Age at Testing	Age of Exposure to		Age of Literacy Acquisition		Parents' Native Language(s)	Language Proficiency Screening (Mean)	
	Mean	English	Spanish	English	Spanish		English	Spanish
Bilinguals	19	birth–5	birth	5–7	5–7	English and Spanish	96.5%	93.4%
Monolinguals	20	birth	NA	5–7	NA	English only	96.3%	NA

in Spanish and in English and equally active in both communities, as per formal assessment of their patterns of language background and use (below). All bilinguals report continued maintenance of both languages since childhood. To ensure equal proficiency/fluency, and equal grammatical competence in each of their native languages, all bilingual participants were required to complete a language screening task, Language Competence/Expressive Proficiency (LCEP, described below), with 80% accuracy or above in each of their languages.

Monolingual English participants were raised in monolingual English families, attended monolingual English schools, and had no exposure to languages other than English until after age 7. After age 7, the monolinguals' second-language exposure was restricted to formal foreign language classes and/or to tourist visits to other countries. All monolingual participants completed the same language competency/proficiency task in English (LCEP), with at least 80% accuracy. All participants received monetary compensation for their time. For all participants, all experimental procedures abided by the ethical guidelines of Dartmouth College's Ethical Review Board.

## Participant Screening

### *Assessment of Bilingual Language Background and Use*

All participants first were administered a Bilingual Language Background and Use screening questionnaire to provide confidence in our “bilingual” (early-exposed, highly proficient) and “monolingual” group assignments (as used in, e.g., Penhune, Cismaru, Dorsaint-Pierre, Petitto, & Zatorre, 2003; Petitto et al., 2000). The screening tool permitted us to determine the *age* of first bilingual exposure, languages used during/throughout schooling, language(s) of reading instruction, and language maintenance (languages of the home in early life and languages used throughout development up until the present).

## Language Competence Assessment

### *Language Competence/Expressive Proficiency (LCEP)*

This task was administered to assess participants' language competence, production, and proficiency (or fluency) in each of their languages, and has been used to assess proficiency/competency across many languages

(e.g., Petitto & Kovelman, 2003; Petitto et al., 2000; Senghas & Kegl, 1994). The task includes two 1-min cartoons with a series of events that the participant watches and then describes to an experimenter. Monolingual participants described each of the two cartoons in English and bilingual participants described one of the cartoons in Spanish to a native Spanish-speaker and one of the cartoons in English, to a different experimenter, who was a native English-speaker (order of language presentation and cartoons was randomized across participants). Sessions were videotaped and native speakers of English and Spanish transcribed the tapes.

Individuals trained as linguistic coders identified utterances within the transcripts and coded each utterance. For English, an “utterance” had to include an overt noun and verb. For Spanish, a pro-drop language, each “utterance” had to include either an overt noun and a verb or just a verb with the proper noun (subject) information embedded in its form. The coding method yielded a total number of utterances produced by each participant in each language. Following this, transcripts were coded for the presence or absence of semantic, phonological, syntactic, and morphological errors, as well as cross-linguistic influence (i.e., code-switching, or utterances that contain linguistic structures that are inconsistent with the target language, but are consistent with the other language of the bilingual, e. g., “Y entra a una finca no se o algo donde *have* muchos *chickens* y pollos.”). The analysis was conducted on the percentage of correct utterances. Each participant was required to produce at least 80% correct utterances in each of her or his languages in order to participate in the experiment. Interrater reliability for both transcription and coding for a subset of participants (25%) was 98.0%.

## Sentence Judgment Task Presented in the Scanner

While in the scanner, the participants were presented with the “sentence judgment task” described earlier. Monolinguals were presented with 40 sentences in English, and bilinguals were presented with the same 40 sentences in English and 40 additional sentences in Spanish. The English sentences were taken directly from David Caplan's set of English stimuli (Caplan et al., 1996). The Spanish sentences were also selected from Caplan's English stimuli and then translated into

Spanish. The SO/OS syntactic organization in the English sentences was preserved in the Spanish stimuli. Half of the sentences of each type were plausible and half were implausible (e.g., plausible: “The sailor that the lighthouse guided piloted the boat”; “El marinero que el faro guió condujo el barco”; and implausible: “The comedian that the joke told upset the woman”; “El comediante que el chiste contó molestó a la mujer”). The kind of semantic violation that made sentences implausible in English was also preserved in the Spanish sentence stimuli—with all confirmed both by linguists who were experts in Spanish language structure and by Spanish informants. Prior to conducting fMRI, the sentences were piloted behaviorally with a group of 18 bilinguals (different from those who participated in the experiment) to ensure that participants were equally comfortable and accurate with English and Spanish stimuli. The experimental participants judged whether the sentences were plausible or not and their behavioral responses as well as fMRI blood oxygen level-dependent (BOLD) signals were measured.

### *Syntactic versus Semantic Properties of the Stimuli*

Measures were taken to ensure that the stimuli were addressing primarily cross-linguistic differences in morphosyntactic rather than semantic processing (summarized in Caplan, 2001). Implausibility in SO and OS sentences was dependent upon the incompatibility between the animacy of a noun phrase and the requirements of a verb. Thus, although the sentences varied in their syntactic complexity, semantic content remained constant. Another important feature of the stimuli was that the sentence types consisted of words that were counterbalanced for length and frequency, and varied in the animacy of the nouns and their position in the sentence to prevent participants from using nonsyntactic (e.g., semantic or thematic) strategies. Finally, in order to further minimize any semantic interference stemming from vocabulary, the words used in the SO and OS sentences were the same.

### **Stimuli Presentation**

We used an Apple G4 Laptop running PsyScope software in order to present the stimuli and record behavioral responses (MacWhinney, Cohen, & Provost, 1997). The participants saw the stimuli in a mirror mounted on top of the head coil; the mirror reflected images from the screen positioned at the head end of the bore; an Epson (model ELP-7000) LCD projector was used to project the images onto the screen. Cushions were placed around the participant's head to minimize movement.

This study employed a block-design method, with each sentence type and each language grouped by block. Thus, during each run, monolinguals were pre-

sented with one English OS and one English SO block. During each run, bilinguals were presented with one block each of English OS, English SO, Spanish OS, and Spanish SO. Half the participants completed blocks in Spanish first and in English second, half the participants had a reversed language order. Explicit warnings about the language of each upcoming block were communicated to participants, and we were careful not to use any presentation of the two languages in rapid alternation (i.e., language switching). Each block contained at least one plausible sentence and at least one implausible sentence, with varying and counterbalanced ratios of plausible/implausible sentences per block. Within the blocks, each sentence was presented for 5 sec with a 1-sec intertrial interval during which a fixation cross was displayed. Participants were instructed to respond as accurately and as quickly as possible. The duration of both block and interblock rest/fixation was 24 sec. There were a total of 5 functional runs. It was key that the English condition be maximally similar across bilinguals and monolinguals. Therefore, we opted not to present monolinguals with extra English stimuli just to equate the length of runs across the groups. In this manner, we avoided providing monolinguals with any extra practice with English sentences. Participants indicated their plausibility/implausibility judgment decision by pressing a right-hand or a left-hand button. Practice trials (different from experimental trials) were administered to participants in each language outside the scanner before the scanning session to insure their familiarity with the instructions and the paradigm.

### *Avoidance of Recruitment of Language Switching Mechanisms*

Measures were taken to prevent effects of language switching in bilinguals. (1) During each run, participants were first presented with SO and OS blocks in one language and then with SO and OS blocks in their other language, separately, to avoid the recruitment of language-switching behavioral and neural mechanisms. (2) The beginning of blocks in a different language was signaled in advance and (3) this predictable language order was practiced before scanning. (4) Task instructions preceding the blocks were provided in the same language as the blocks to ensure *priming* of the correct language.

### **fMRI Data Acquisition**

The experiment was performed on a General Electric Horizon whole-body “Echospeed” 1.5-T MRI scanner with a standard head coil. Following the collection of a localizer, T1-coplanar, and spoiled gradient (SPGR) anatomical images, two T2-weighted echo planar (EPI) functional time series were collected. EPI data collection parameters were as follows: TR = 2000 msec, TE = 50 msec,

FOV = 24 cm, matrix size =  $64 \times 64$ , number of slices = 26, slice thickness = 4.5 mm (skip 1 mm). SPGR anatomical image volume parameters were number of echoes = 1, TR = 7.7 msec, TE = 3.0 msec, flip angle =  $15^\circ$ , BW = 31.25 MHz, FOV = 240 mm, slice thickness = 1.2 mm, matrix size =  $256 \times 192$ , NEX = 2. There was a total of 5 functional runs, allowing a total of 565 functional EPI volumes for bilinguals and 320 for monolinguals.

## fMRI Data Preprocessing and Analysis

The data were preprocessed and analyzed using Statistical Parametric Mapping tools (SPM99, Wellcome Department of Cognitive Neurology, London, UK; Friston et al., 1995).

### Preprocessing

We corrected for motion by motion correction to the first functional scan. Motion correction was performed within subject, using a six-parameter rigid-body transformation. The mean of the motion-corrected images was coregistered to the individual's coplanar MRI using mutual information, followed by coregistration of the coplanar and high-resolution structural MRIs. The high-resolution MRI (followed by the coregistered functional images) was then spatially normalized to the Montreal Neurological Institute (MNI; Evans et al., 1992) template by applying a 12-parameter affine transformation followed by a nonlinear warping using basis. The spatially normalized functional scans were then smoothed with a 6-mm isotropic Gaussian kernel to accommodate anatomical differences across participants.

### Analysis

Images were analyzed and contrasted according to a block-design model, in which the magnitude of the BOLD effect was measured in terms of when the subject was actively performing the task blocks, minus the BOLD effect for the rest periods. Design matrices for participants included columns for each language and condition (English SO, English OS, Spanish SO, and Spanish OS) and were regressed against the preprocessed functional imaging data via the general linear model (GLM). Random effects methods were employed for group analysis. The description of stimulus apparatus, preprocessing, and analysis is based upon Van Horn, Yanos, Schmitt, and Grafton (2006).

## RESULTS

### Behavioral Results

#### Reaction Time Analysis

This analysis revealed that there was a main effect of language group and no main effect of sentence type. Bilinguals in English performed with the same speed as English monolinguals as per each sentence type. Bilinguals' RTs in English were different from their RTs in Spanish. As revealed by a 3 [RT (monolinguals' and bilinguals' (English and Spanish), between factor)]  $\times$  2 [sentence type (SO and OS, within factor)]  $\times$  2 [plausibility (plausible and implausible, within factor)] mixed analysis of variance (ANOVA), there was a main effect of language group [ $F(2, 29) = 7.89, p < .01$ ] and no main effect of sentence type [ $F(1, 29) = 5.89, p > .01$ ]. There was also a main effect of plausibility: Overall, participants performed significantly faster on plausible sentences

**Table 2.** Monolinguals and Bilinguals Performed More Accurately and More Rapidly on OS Sentences Than SO Sentences, in Each of Their Languages ( $p < .05$ )

Group/Language	% Correct		RT (msec)	
	Mean (SD)		Mean (SD)	
	SO	OS	SO	OS
Monolinguals	85.0 (11.3)	94.4 (6.0)	3600 (539)	3364 (402)
Plausible	76.1 (16.0)	94.6 (10.3)	3536 (461)	3226 (377)
Implausible	90.8 (11.4)	94.1 (7.7)	3634 (612)	3624 (538)
Bilinguals English	85.2 (8.6)	88.5 (8.3)	3857 (542)	3708 (353)
Plausible	77.3 (9.0)	85.2 (9.4)	3880 (603)	3701 (348)
Implausible	90.5 (10.6)	94.6 (7.5)	3801 (507)	3736 (479)
Bilinguals Spanish	84.9 (6.4)	86.7(12.0)	4229 (304)	4147 (404)
Plausible	86.8 (8.2)	91.2 (10.9)	4095 (363)	3903 (440)
Implausible	82.0 (17.8)	83.7 (16.5)	4450 (448)	4307 (444)

In English, bilinguals and monolinguals performed with the same speed on each type of sentences ( $p > .05$ ). In Spanish, bilinguals performed significantly slower than in English on OS sentences, and were overall slower than English monolinguals on each sentence type ( $p < .05$ ).



**Table 3.** Brain Regions Activated in Monolinguals and Bilinguals (in English and in Spanish) in Task > Baseline Contrast

<i>Anatomical Location</i>		<i>Left Hemisphere</i>				<i>Right Hemisphere</i>			
<i>Gyrus/Brain Area</i>	<i>BA</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>
<i>Inferior frontal</i>	47/11								
Monolinguals English		−46	26	−6	7.01				
Bilinguals English		−44	22	−8	5.63				
Bilinguals Spanish		−34	30	−6	8.26				
	44/45								
Monolinguals English		−56	16	14	6.7	52	18	26	7.12
Bilinguals English		−46	20	14	7.57	52	24	12	6.16
Bilinguals Spanish		−52	10	4	12.45				
<i>Insula</i>									
Monolinguals English		−32	24	2	5.45	36	24	−2	5.22
Bilinguals English		−36	18	0	9.09	36	26	−6	9.16
Bilinguals Spanish		−28	20	−2	8.8	36	28	−4	9.78
<i>Middle frontal</i>	6								
Monolinguals English		−44	0	38	14.65				
Bilinguals English		−40	−4	48	19.5				
Bilinguals Spanish		−52	0	48	15.17	34	4	48	6.04
<i>Superior frontal</i>	6								
Monolinguals English		−48	12	26	12.9	52	18	26	7.12
Bilinguals English		−4	10	58	14.52				
Bilinguals Spanish		−8	8	72	11.59				
<i>Superior temporal</i>	21/22								
Monolinguals English		−48	−48	22	9.66				
Bilinguals English		−50	−50	12					
Bilinguals Spanish		−50	−48	14					
<i>Middle temporal</i>	21								
Monolinguals English		−52	−30	−4	10.58				
Bilinguals English		−50	−52	6	7.27				
Bilinguals Spanish		−50	−52	4	10.12				
<i>Supramarginal and postcentral</i>	7/40								
Monolinguals English		−28	−60	50	6.11	30	−64	52	5.03
Bilinguals English		−44	−44	44	10.7	30	−64	50	8.7
Bilinguals Spanish		−40	−46	40	5.96	32	−66	44	11
<i>Fusiform</i>	37								
Monolinguals English		−42	−66	−16	6.25				

**Table 3.** (continued)

Anatomical Location		Left Hemisphere				Right Hemisphere			
Gyrus/Brain Area	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>
Bilinguals English		-44	-58	-22	9.24				
Bilinguals Spanish		-44	-58	-22	19.61				
<i>Occipital</i>	28								
Monolinguals English		-22	-94	-18	8.97	36	-80	-12	5.91
Bilinguals English		-20	-96	-16	8.06	20	-94	-8	5.35
Bilinguals Spanish		-10	-78	6	5.04	20	-94	-8	5.82
<i>Cerebellum</i>									
Monolinguals English		-28	-66	-28	8.8	32	-64	-32	12.62
Bilinguals English		-38	-72	-34	12.21	36	-68	-36	19.03
Bilinguals Spanish		-44	-58	-22	19.61	28	-74	-36	14.57

Listed areas of activation survived the significance threshold set at  $p < .001$ , uncorrected; cluster size  $k > 10$  voxels; BA = Brodmann's area; MNI coordinates are being reported; left superior temporal gyrus activations in bilinguals were insignificant at this threshold, but are reported here for completeness.

than on implausible sentences [ $F(1, 29) = 13.60$ ,  $p < .01$ ]. There were no significant interactions ( $p > .01$ ). Post hoc Tukey Honest Difference (HD) analysis revealed that in English, bilinguals performed with the same speed as English monolinguals (henceforth "monolinguals") on each type of sentence ( $p > .01$ ). On OS sentences, bilinguals performed slower in Spanish than in English ( $p < .05$ ). Overall, bilinguals performed slower than monolinguals on each sentence type ( $p < .05$ ; Table 2).

#### Accuracy Analysis

This analysis revealed that there was no accuracy difference between the language groups and bilinguals in English, like monolinguals in English, performed better on OS than on SO sentences. As revealed by a 3 [accuracy scores (monolinguals' and bilinguals' (English and Spanish), between factor)  $\times$  2 [sentence type (SO and OS, within factor)]  $\times$  2 [plausibility (plausible/implausible, within factor)] mixed ANOVA, there was no difference between the language groups [ $F(2, 29) = 0.65$ ,  $p > .01$ ]. All participants performed better on OS than on SO sentences [ $F(1, 29) = 12.12$ ,  $p < .01$ ]. This difference in OS versus SO performance was the greatest for monolinguals and the smallest for bilinguals in Spanish (Table 2). There was no significant difference between plausible and implausible sentences [ $F(1, 29) = 4.26$ ,  $p > .01$ ]. There was a significant Plausibility by Language group interaction [ $F(2, 29) = 7.29$ ,  $p < .01$ ], showing that in English, both groups performed slightly more accurately on implausible sentences, whereas Spanish participants performed slightly more accurately

on the plausible sentences (see all the scores and RTs in Table 2). Interestingly, across both plausible and implausible sentences, monolinguals and bilinguals in English performed better on the OS sentences (as would be predicted from the fact that OS is the most "unmarked," most prevalent sentence type in English, a language that uses predominantly word-order changes to signal changes in meaning). However, in Spanish, bilinguals' accuracy was almost the same for OS and SO sentences (as would be predicted from Spanish's predominant use of morphology-over word-order-to signal changes in meaning). Said another way, English monolinguals show the accuracy asymmetry between OS versus SO sentences; bilinguals also show the same accuracy asymmetry in English, but they do not show it in Spanish. Together, these behavioral findings are powerfully predicted from the differences between Spanish and English grammatical structures, providing support that the Spanish-English bilinguals are differentiating their two languages.

#### Neuroimaging Results

##### Task versus Baseline (Sentence Judgment Task vs. Fixation Cross)

Bilingual and monolingual participants activated the same classic language areas, as well as predicted vision and motor areas. Table 3 lists brain activations during OS/SO tasks combined, for bilinguals (in Spanish and in English) and monolinguals; these brain activations survived the significance threshold set at  $p < .001$  (uncorrected), cluster size  $k > 10$ . We observed an increase in BOLD signal

intensity within the LIFC (particularly within BA 44/45) in *both* bilinguals and monolinguals. The increase in BOLD signal intensity for both groups is consistent with previous research on syntactic processing in monolinguals alone (Caplan, 2001; Friederici, 2001).

### Monolinguals versus Bilinguals

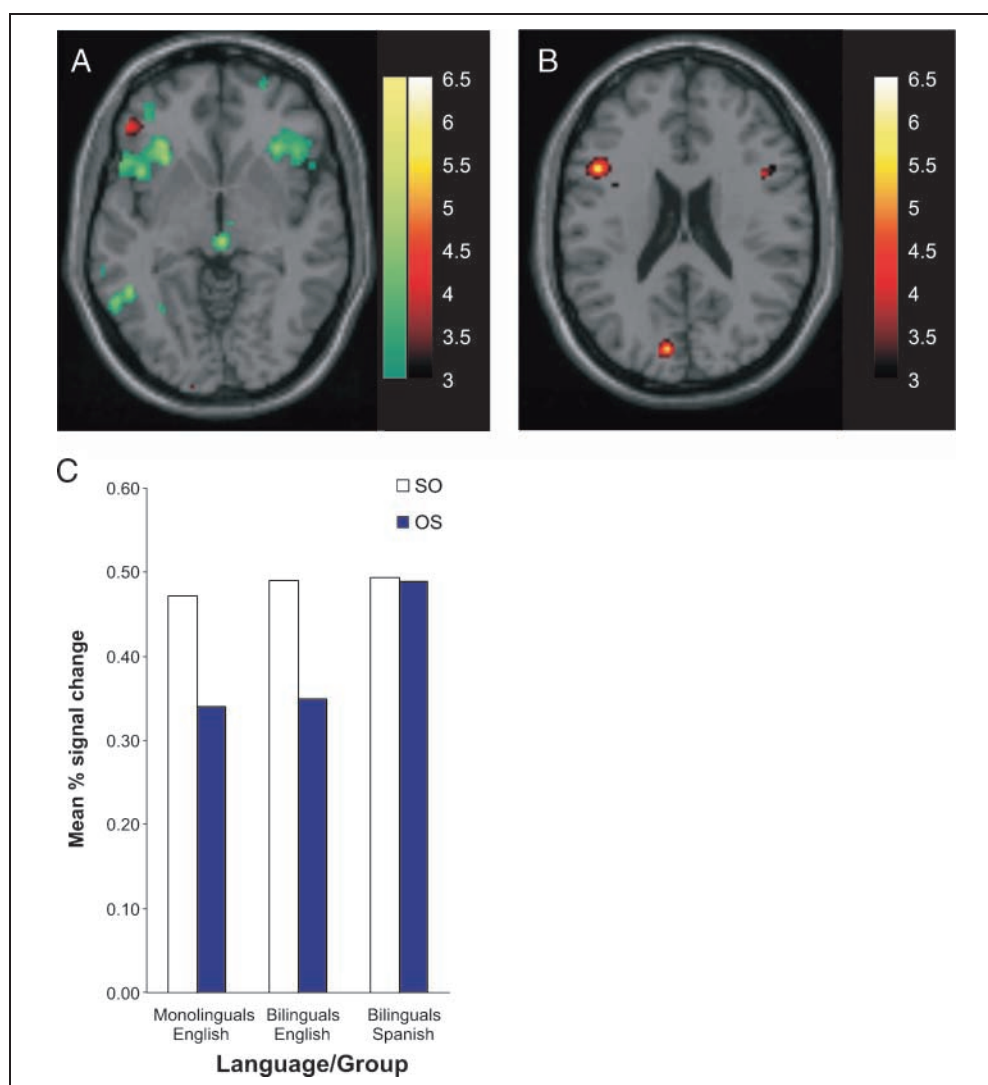
Differences in the BOLD signal intensity and location/extent were found between bilingual and monolingual participants on the English > baseline comparisons. Bilingual participants revealed greater BOLD signal intensity and extent in the LIFC [BA 45; Figure 1A;  $t(1, 10) = 2.86$ ; the activations survived the significance threshold set at  $p < .001$  (uncorrected), cluster size  $k > 10$ ]. Subtraction in the opposite direction, monolinguals versus bilinguals, revealed no differences in activation. To ensure that this difference between bilinguals and monolinguals was true of all participants, we conducted a set of correlation analyses between bilinguals' activa-

tion on this contrast and their age of first bilingual exposure, type of schooling before college, and behavioral performance on the sentence judgment task in English and in Spanish. All correlations were nonsignificant ( $p > .05$ ), confirming that our bilinguals were, indeed, a homogenous group of highly proficient, early-exposed balanced bilinguals.

### Spanish versus English in Bilinguals

Overall, with brain activation for SO and OS sentences combined, bilinguals had similar activations across both of their languages [the activations for the SO plus OS English vs. Spanish contrast did not survive the significance threshold set at  $p < .001$  (uncorrected), cluster size  $k > 10$ ], which is consistent with previous research showing that early bilinguals process both of their languages within overlapping neuronal networks (Chee, Soon, & Lee, 2003; Kim et al., 1997). Importantly, note the detailed description below of the differences in the

**Figure 1.** (A) LIFC activation in bilinguals > monolinguals contrast for English language (BA 45;  $x = -48, y = 38, z = -4, t = 4.35, p < .001$ , uncorrected; cluster size  $k > 10$  voxels) Hot/red colors refer to activation unique to bilinguals, spring/green colors refer to the shared activation between bilinguals and monolinguals on the syntactic task in English. (B and C) ROI analysis of LIFC activation for SO and OS sentences in monolinguals in English and bilinguals in English and Spanish (BA 44;  $x = -46, y = 16, z = 24, t = 6.18$ ; Tukey HSD,  $p < .05$ ). Color scale represents  $t$  value.



bilinguals' brain activation between Spanish and English during SO versus OS trials.

### Sentence Types

While in English mode, both bilinguals and monolinguals showed greater BOLD signal intensity across several regions of the brain; within the predicted LIFC region (BA 45), the intensity was greater for SO ("diffi-

cult") than for OS ("easy") sentences [Table 4;  $t(1, 10) = 4.14$  and  $t(1, 9) = 4.30$ , respectively, significance threshold set at  $p < .001$  (uncorrected), cluster size  $k > 10$ ]. In Spanish mode, bilinguals showed no differences in brain activity during the SO versus OS sentences [that is, no activation survived the significance threshold set at  $p < .001$  (uncorrected), cluster size  $k > 10$ ]. Together, these results are consistent with the accuracy results reported above. Moreover, bilinguals showed greater

**Table 4.** Brain Regions Activated in Monolinguals and in Bilinguals in English in SO > OS Contrast

Anatomical Location		Left Hemisphere				Right Hemisphere			
Gyrus/Brain Area	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>
<i>Inferior frontal</i>									
Monolinguals	44/45	-50	16	10	8.66	40	38	20	8.03
Bilinguals		-56	14	4	5.13				
<i>Insula</i>									
Monolinguals									
Bilinguals		-42	14	-4	4.85	34	26	-10	6.27
<i>Inferior frontal</i>									
Monolinguals	47					56	16	0	5.83
Bilinguals									
<i>Middle frontal</i>									
Monolinguals	46					40	38	20	8.03
Bilinguals						56	28	32	6.95
<i>Middle frontal</i>									
Monolinguals	6	-26	8	52	6.09				
Bilinguals		-14	26	40	6.13				
<i>Superior frontal</i>									
Monolinguals	6	-8	10	54	4.91	10	4	68	5.77
Bilinguals		-18	18	54	6.54				
<i>Angular</i>									
Monolinguals	19								
Bilinguals						40	-78	36	5.62
<i>Cerebellum</i>									
Monolinguals		-20	-52	-24	5.06				
Bilinguals		-20	-80	-38	5.6	20	-66	-38	4.81

The areas of activation presented below survived the significance threshold set at  $p < .001$ , uncorrected; cluster size  $k > 10$  voxels; BA = Brodmann's area; MNI coordinates are being reported.



BOLD signal in the LIFC (BA 44;  $x = -46, y = 16, z = 24, t = 6.18$ ) and left precentral gyrus (BA 6;  $x = -44, y = 4, z = 46, t = 6.65$ ) when processing OS, the “easy” word order sentences, in Spanish as opposed to English [ $t(1, 9) = 4.30$ , significance threshold set  $p < .001$  (uncorrected), cluster size  $k > 10$ ]. There was no significantly greater activation in the OS > SO contrast for either of the groups in either of the languages [no activation survived the significance threshold set at  $p < .001$  (uncorrected), cluster size  $k > 10$ ].

Region-of-interest analysis (ROI) was applied to explore participants’ activation within the predicted region of the LIFC (BA 44/45) across the two sentence types. This LIFC (BA 44/45) region was chosen due to its key role in syntax processing and because it has been previously shown to have higher activation during SO versus OS sentences (Caplan, 2001; Caplan et al., 1998; Stromswold et al., 1996). From the following contrasts, we empirically derived three LIFC (BA 44/45) regions for the ROI analysis: (1) bilinguals’ Spanish OS > English OS contrast; (2) monolinguals’ SO > OS contrast; and (3) bilinguals’ English SO > OS contrast. ROI analysis using Tukey HD post hoc procedures revealed that for the first ROI (LIFC, BA 45), bilinguals and monolinguals had higher activity during SO versus OS sentences in English ( $p < .05$ ), but bilinguals had the same level of activity across SO and OS sentences in Spanish ( $p > .05$ ; Figure 1B and C). A similar pattern held for the other two LIFC (BA 45) regions (2 and 3) as well as their right hemisphere homologues. Thus, in English, bilinguals showed changes in brain activity consistent with increases in word-order complexity, whereas in Spanish no such modulation in brain activity was observed. These findings are consistent both with the sentence type imaging analysis as well as with the pattern of behavioral (accuracy) results (both discussed above).

## DISCUSSION

Both the bilingual group’s behavioral performance and neural activity were different depending upon whether they were processing in English versus processing in Spanish, providing new support for the view that bilinguals have differentiated neural representation of their two languages. Behaviorally, regarding speed, bilinguals in English and English monolinguals performed similarly on the sentence judgment task, and, crucially, bilinguals showed the same speed differences depending upon the English sentence type (OS vs. SO, whereupon the more unmarked sentence structure, OS, was faster across language groups). By contrast, in Spanish, bilinguals’ behavioral performance demonstrated an overall slower processing speed as compared to English (including bilinguals in English and monolinguals in English). Regarding accuracy, bilinguals in English and English monolinguals performed similarly (OS was more accurate than SO), reflecting the English language’s heavy

reliance on word-order changes to change meaning. In addition, there were no such sentence type accuracy differences evident in Spanish, whose grammatical structure relies more heavily on morphological changes to change meaning.

Regarding the neuroimaging data, especially as revealed in the monolingual versus bilingual and sentence type subtractions, both the bilinguals and monolinguals showed an increase in BOLD signal intensity within the LIFC (particularly within BA 44/45) during the sentence judgment task. However, there was an important difference: In English, bilingual participants revealed a greater BOLD signal intensity as well as a greater extent in LIFC recruitment (BA 45; Figure 1A) than observed in English monolinguals processing English. This intriguing finding would have been lost if one were observing the behavioral data alone. To be sure, the behavioral data did not reveal the whole story. While the behavioral data showed processing differences when bilinguals were in Spanish versus in English modes, only the neuroimaging data revealed the remarkable observation that bilinguals were recruiting a greater extent of the brain’s classic language processing tissue than monolinguals (more below). Finally, the sentence type subtractions revealed that bilinguals show an English neural profile when processing English (as they show activation differences as a function of English sentence type difficulty) and they show a Spanish neural profile in Spanish. Here, as predicted, they do not show activation differences in Spanish as a function of sentence type because word order is more variable in Spanish, thus neither sentence type is more “difficult.”

Previous neuroimaging studies have shown that English monolinguals have higher LIFC (BA 44/45) activation for the more complex (“harder”) SO rather than for the less complex (“easier”) OS relative clause sentences (Caplan, 2001; Caplan et al., 1998; Stromswold et al., 1996), and this was also observed here in our bilingual and monolingual participants when processing in English, but (appropriately so) not in Spanish. Moreover, our observations of the bilingual participants in Spanish-only mode are consistent with previous behavioral studies of Spanish language processing (Fernandez, 2002; Bates et al., 1999; Hernandez et al., 1994; MacWhinney & Bates, 1989). In Spanish, a romance language where monolingual speakers make heavier reliance on verb morphology than word order when judging a relative clause sentence (Bates et al., 1999), one would expect no differences in brain activity between the two sentence types with varying word order. This is exactly what we observed in our bilinguals in Spanish. As such, in our participants, their bilingual brains honored the grammatical distinction between their two languages. Thus, although adult bilinguals may show behavioral evidence of cross-linguistic interference (Hernandez et al., 1994), early bilinguals with extensive dual-language exposure may, nonetheless, develop predominantly differentiated representations for each of their languages in one brain.

The present results provide insights into the decades-old question about the degree of separation of bilinguals' dual-language representation. That the bilinguals showed processing differences in English versus Spanish, which were specifically predicted from differences in the linguistic structures typical of English versus Spanish, lends support to the hypothesis that bilinguals can develop two differentiated, monolingual-like, linguistic systems in one brain. Moreover, the findings offer novel insights into the previously unresolved one "fused" versus two "differentiated" linguistic systems debate in bilingual language processing by discovering evidence that bilinguals have a *differentiated* neural pattern of activation for each language. A concern among educators is that early exposure to two languages might be a source of fundamental and persistent language confusion, and life-long fragmentary linguistic knowledge, resulting from having experienced "language contamination" (or, exposure to two languages too early in life; e.g., Crawford, 1999). The present findings that early-exposed, adult bilinguals show differential and *normal* language processing in each of their two languages do not support this belief.

To the best of our knowledge, few studies have directly compared neural language processing in healthy, early-exposed, and highly proficient bilinguals versus monolinguals, while the groups processed only one language at a time rather than switching between the two (i.e., Proverbio, Cok, & Zani, 2002). In the Proverbio et al. study, they studied proficient Italian-Slovenian birth bilinguals using ERP with a different sentence processing task than the one used here. As in the present study, they found that their Italian-Slovenian bilinguals in Italian had a similar neural response as compared to Italian monolinguals. Furthermore, a structural MRI study by Mechelli et al. (2004) showed that early and highly proficient bilinguals had the most extensive enlargement of the left inferior parietal cortex as compared to monolinguals. Thus, a functional ERP study with excellent temporal resolution, a detailed structural anatomical MRI study, and our fMRI study reported here converge on the common finding that the human neural organization and language processing capacity can be molded by extensive dual-language exposure early in life (Mayberry, Lock, & Kazmi, 2002; Newman et al., 2002; Neville & Bavelier, 2001; Petitto & Bellugi, 1988).

Up until the present study, some researchers have proposed that early, highly proficient bilinguals have identical brain activation across their two languages (Chee et al., 2003; Kim et al., 1997). Consistent with previous neuroimaging research, our early, highly proficient bilinguals demonstrated overlapping and similar neural activations across their two languages. What is new about the present study is that we also observed neural differences between the bilingual's two languages in the same bilingual brain. We suggest that the differ-

ences between the bilinguals' two languages involved the intensity with which each of their languages recruited the LIFC (BA 44/45). What was even more fascinating about the observed differences is that they were principled, predictable, and governed by the morphosyntactic differences that exist between the specific languages at hand. Thus, the present study provides neural evidence suggesting that there may be a functional separation of a bilingual's two languages in one brain *based on* the formal linguistic properties of each given languages.

In a further surprising and unexpected twist, we observed a greater extent of recruitment of the LIFC in bilinguals processing English as compared with monolinguals processing English. Why would bilinguals require a greater extent of LIFC recruitment than monolinguals? Might this area be the seat of a language separation mechanism for bilinguals (Penfield & Lamar, 1959)? Alternatively, might these results reveal something else about the potential extent of language-dedicated neural tissue that can be neurally modified through experience when an individual is presented with two languages rather than one early in life? Indeed, we suggest that this finding provides a fascinating window into the language processing potential not fully recruited in monolingual brains and further suggests the biological extent of the neural architecture underlying all human language.

## Acknowledgments

We thank Scott Grafton (former Director, Dartmouth Functional Brain Imaging Center) for assistance with the fMRI data analyses. We thank Katherine White, post-doctoral fellow in the Petitto Laboratory, for her close reading of and suggestions relating to an earlier version of this manuscript. We also extend our sincere thanks to all the members of the Dartmouth Brain Imaging Center and to Joe Moran. We are greatly indebted to David Caplan (Harvard Medical School) for his generosity in sharing his research sentence stimuli with us. L. A. Petitto thanks especially the U.S.A.'s National Institutes of Health for her two grants that funded this research: R01 HD 045822-03, and R21 HD 050558-02.

Reprint requests should be sent to Laura-Ann Petitto, Department of Psychology, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON, Canada, M1C 1A4, or via e-mail: [petitto@utsc.utoronto.ca](mailto:petitto@utsc.utoronto.ca); Website: <http://www.utsc.utoronto.edu/~lpetitto/>.

## REFERENCES

- Ameel, E., Storms, G., Malt, B. C., & Sloman, S. A. (2005). How bilinguals solve the naming problem. *Journal of Memory and Language*, 53, 60–80.
- Bates, E., Devescovi, A., & D'Amico, S. (1999). Processing complex sentences: A cross-linguistic study. *Language Cognitive Processes*, 14, 69–123.
- Bates, E., & MacWhinney, B. (1989). Functionalism and the competition model. In B. MacWhinney & E. Bates (Eds.), *The*

- crosslinguistic study of sentence processing* (pp. 3–73). Cambridge: Cambridge University Press.
- Blackwell, A., Bates, E., & Fisher, D. (1996). The time course of grammaticality judgment. *Language and Cognitive Processes*, 11, 337–406.
- Caplan, D. (2001). Functional neuroimaging studies of syntactic processing. *Journal of Psycholinguistic Research*, 30, 297–320.
- Caplan, D., Alpert, N., & Waters, G. (1998). Effects of syntactic structure and propositional number on patterns of regional cerebral blood flow. *Journal of Cognitive Neuroscience*, 10, 541–552.
- Caplan, D., Alpert, N., Waters, G., & Olivieri, A. (2000). Activation of Broca's area by syntactic processing under conditions of concurrent articulation. *Human Brain Mapping*, 9, 65–71.
- Caplan, D., Hildebrandt, N., & Makris, N. (1996). Location of lesions in stroke patients with deficits in syntactic processing in sentence comprehension. *Brain*, 1, 933–949.
- Caplan, D., Waters, G., & Alpert, N. (2003). Effects of age and speed of processing on rCBF correlates of syntactic processing in sentence comprehension. *Human Brain Mapping*, 19, 112–131.
- Chee, M. W., Caplan, D., Soon, C. S., Sriram, N., Tan, E. W., Thiel, T., et al. (1999). Processing of visually presented sentences in Mandarin and English studied with fMRI. *Neuron*, 23, 127–137.
- Chee, M. W., Soon, C. S., & Lee, H. L. (2003). Common and segregated neuronal networks for different languages revealed using functional magnetic resonance adaptation. *Journal Cognitive Neuroscience*, 15, 85–97.
- Chee, M. W., Soon, C. S., Lee, H. L., & Pallier, C. (2004). Left insula activation: A marker for language attainment in bilinguals. *Proceedings of the National Academy of Sciences, U.S.A.*, 101, 15265–15270.
- Crawford, J. (1999). *Bilingual education: History, politics, theory, and practice* (4th ed.). Los Angeles, CA: Bilingual Educational Services.
- Dapretto, M., & Bookheimer, S. Y. (1999). Form and content: Dissociating syntax and semantics in sentence comprehension. *Neuron*, 24, 427–432.
- De Bleser, R., Dupont, P., Postler, J., Bormans, G., Spelman, D., Mortelmans, L., et al. (2003). The organization of the bilingual lexicon: A PET study. *Journal of Neurolinguistics*, 16, 439–456.
- de Groot, A. M. B. (1992). Bilingual lexical representation: A closer look at conceptual representations. *Advances in Psychology. Orthography, Phonology, Morphology, and Meaning*, 94, 389–412.
- De Houwer, A. (1999). Language acquisition in children raised with two languages from birth: An update. *Revue Parole*, 9, 63–88.
- Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., et al. (1997). Anatomical variability in the cortical representation of first and second language. *NeuroReport*, 8, 3809–3815.
- Dijkstra, T., & Van Heuven, W. J. B. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language & Cognition*, 5, 175–197.
- Doepke, S. (Ed.) (2000). *Cross-linguistic structures in simultaneous bilingualism*. Amsterdam, Netherlands: John Benjamins Publishing Company.
- Evans, A. C., Marrett, S., Neelin, P., Collins, L., Worsley, K., Dai, W., et al. (1992). Anatomical mapping of functional activation in stereotactic coordinate space. *Neuroimage*, 1, 43–53.
- Fennell, C., Byers-Heinlein, K., & Werker, J. A. (2006). *Comprehensive analysis of bilingual infants' use of phonetic detail in words*. Presented at Language Acquisition and Bilingualism Conference, Toronto, Canada, May 2006.
- Fernandez, E. M. (2002). *Bilingual sentence processing: Relative clause attachment in English and Spanish*. Philadelphia: John Benjamins Publishing Company.
- Flège, J. E., MacKay, I. R. A., & Meador, D. (1999). Native Italian speakers' perception and production of English vowels. *Journal of the Acoustical Society of America*, 106, 2973–2987.
- Foundas, A. L., Eure, K. F., Luevano, L. F., & Weinberger, D. R. (1998). MRI asymmetries of Broca's area: The pars triangularis and pars opercularis. *Brain & Language*, 64, 282–296.
- Frenck-Mestre, C., Anton, J. L., Roth, M., Vaid, J., & Viallet, F. (2005). Articulation in early and late bilinguals' two languages: Evidence from functional magnetic resonance imaging. *NeuroReport*, 16, 761–765.
- Friederici, A. D. (2001). Syntactic, prosodic, and semantic processes in the brain: Evidence from event-related neuroimaging. *Journal of Psycholinguistic Research*, 30, 237–250.
- Friederici, A. D., Steinhauer, K., & Pfeifer, E. (2002). Brain signatures of artificial language processing: Evidence challenging the critical period hypothesis. *Proceedings of the National Academy of Sciences, U.S.A.*, 99, 529–534.
- Friston, K., Holmes, A., Worsley, K., Poline, J., Frith, C., & Frackowiak, R. (1995). Statistical parametric maps: Linear approach. *Human Brain Mapping*, 2, 189–210.
- Genesee, F. (1989). Early bilingual development: One language or two? *Journal of Child Language*, 16, 161–179.
- Gollan, T. H., & Kroll, J. F. (2001). Bilingual lexical access. In B. Rapp (Ed.), *The handbook of cognitive neuropsychology: What deficits reveal about the human mind* (pp. 321–345). New York: Psychology Press.
- Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, 1, 67–81.
- Grosjean, F. (Ed.) (2001). *The bilingual's language modes*. Malden, MA: Blackwell Publishing.
- Hagoort, P. (2005). On Broca, brain, and binding: A new framework. *Trends in Cognitive Sciences*, 9, 416–423.
- Hahne, A., & Friederici, A. D. (2001). Processing a second language: Late learners' comprehension mechanisms as revealed by event-related brain potential. *Bilingualism: Language & Cognition*, 4, 123–141.
- Hernandez, A. E., Bates, E. A., & Avila, L. X. (1994). On-line sentence interpretation in Spanish–English bilinguals: What does it mean to be “in between”? *Applied Psycholinguistics*, 15, 417–446.
- Hernandez, A. E., Martinez, A., & Kohnert, K. (2000). In search of the language switch: An fMRI study of picture naming in Spanish–English bilinguals. *Brain and Language*, 73, 421–431.
- Holowka, S., Brosseau-Lapr  , F., & Petitto, L. A. (2002). Semantic and conceptual knowledge underlying bilingual babies' first signs and words. *Language Learning*, 52, 205–262.
- Illes, J., Francis, W. S., Desmond, J. E., Gabrieli, J. D. E., Glover, G. H., Poldrack, R., et al. (1999). Convergent cortical representation of semantic processing in bilinguals. *Brain and Language*, 70, 347–363.
- Johnson, J. S., & Newport, E. L. (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognitive Psychology*, 21, 60–99.
- Kim, K. H. S., Relkin, N. R., Lee, K.-M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature*, 388, 171–174.



- Klein, D., Watkins, K. E., Zatorre, R. J., & Milner, B. (2006). Word and nonword repetition in bilingual subjects: A PET study. *Human Brain Mapping*, 27, 153–161.
- Kohnert, K. J., Bates, E., & Hernandez, A. E. (1999). Balancing bilinguals: Lexical-semantic production and cognitive processing in children learning Spanish and English. *Journal of Speech, Language, & Hearing Research*, 42, 1400–1413.
- Kroll, J. F., & Stewart, E. (1994). Category interference in translation and picture naming: Evidence for asymmetric connection between bilingual memory representations. *Journal of Memory and Language*, 33, 149–174.
- Kroll, J. R., & Sunderman, G. (2003). Cognitive processes in second language learners and bilinguals: The development of lexical and conceptual representations. In C. Doughty & M. Long (Eds.), *The handbook of second language acquisition* (pp. 104–129). Oxford: Blackwell.
- Lanza, E. (2000). Concluding remarks: Language contact—A dilemma for the bilingual child or for the linguist? In S. Doepke (Ed.), *Cross-linguistic structures in simultaneous bilingualism*. Amsterdam: John Benjamins Publishing Company.
- Liu, H., Bates, E., & Li, P. (1992). Sentence interpretation in bilingual speakers of English and Chinese. *Applied Psycholinguistics*, 13, 451–484.
- MacWhinney, B., & Bates, E. (1989). *The crosslinguistic study of sentence processing*. New York: Cambridge University Press.
- MacWhinney, B., Cohen, J., & Provost, J. (1997). The PsyScope experiment-building system. *Spatial Vision*, 11, 99–101.
- Mahendra, N., Plante, E., Magloire, J., Milman, L., & Trouard, T. P. (2003). fMRI variability and the localization of languages in the bilingual brain. *NeuroReport*, 14, 1225–1228.
- Marian, V., Spivey, M., & Hirsch, J. (2003). Shared and separate systems in bilingual language processing: Converging evidence from eyetracking and brain imaging. *Brain and Language*, 86, 70–82.
- Mayberry, R. I., Lock, E., & Kazmi, H. (2002). Linguistic ability and early language exposure. *Nature*, 417, 38.
- Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., et al. (2004). Neurolinguistics: Structural plasticity in the bilingual brain. *Nature*, 431, 757.
- Meisel, J. M. (2001). The simultaneous acquisition of two first languages: Early differentiation and subsequent development of grammars. In J. Cenoz & F. Genesee (Eds.), *Trends in bilingual acquisition. Trends in language acquisition research* (pp. 11–41). Amsterdam: John Benjamins Publishing Company.
- Mueller, N., & Hulk, A. (2001). Crosslinguistic influence in bilingual language acquisition: Italian and French as recipient languages. *Bilingualism: Language & Cognition*, 4, 1–21.
- Neville, H. J., & Bavelier, D. (2001). Specificity of developmental neuroplasticity in humans: Evidence from sensory deprivation and altered language experience. In C. A. Shaw & J. C. McEachern (Eds.), *Toward a theory of neuroplasticity* (pp. 261–274). Philadelphia: Psychology Press/Taylor Francis.
- Newman, A. J., Bavelier, D., Corina, D., Jezzard, P., & Neville, H. J. (2002). A critical period for right hemisphere recruitment in American sign language processing. *National Journal of Neuroscience*, 5, 76–80.
- Ni, W., Constable, R. T., Mencl, W. E., Pugh, K. R., Fulbright, R. K., Shaywitz, S. E., et al. (2000). An event-related neuroimaging study distinguishing form and content in sentence processing. *Journal of Cognitive Neuroscience*, 12, 120–133.
- Nicoladis, E. (2002). The cues that children use in acquiring adjectival phrases and compound nouns: Evidence from bilingual children. *Brain and Language*, 81, 635–648.
- Ohnishi, T., Matsuda, H., Asada, T., Aruga, M., Hirakata, M., Nishikawa, M., et al. (2001). Functional anatomy of musical perception in musicians. *Cerebral Cortex*, 11, 754–760.
- Paradis, J., & Navarro, S. (2003). Subject realization and crosslinguistic interference in the bilingual acquisition of Spanish and English: What is the role of the input? *Journal of Child Language*, 30, 371–390.
- Paradis, M. (1977). Bilingualism and aphasia. In H. Whitaker & H. A. Whitaker (Eds.), *Studies in neurolinguistics* (pp. 65–121). New York: Academic Press.
- Paradis, M. (1997). The cognitive neuropsychology of bilingualism. In A. M. B. de Groot (Ed.), *Tutorials in bilingualism: Psycholinguistic perspectives* (pp. 331–354). Mahwah: Erlbaum.
- Pearson, B. Z., Fernandez, S. C., & Oller, D. K. (1993). Lexical development in bilingual infants and toddlers: Comparison to monolingual norms. *Language Learning: A Journal of Applied Linguistics*, 43, 93–120.
- Penfield, W., & Lamar, R. (1959). *Speech and brain-mechanisms*. Princeton, NJ: Princeton University Press.
- Penhune, V. B., Cismaru, R., Dorsaint-Pierre, R., Petitto, L. A., & Zatorre, R. J. (2003). The morphometry of auditory cortex in the congenitally deaf measured using MRI. *Neuroimage*, 20, 1215–1225.
- Perani, D., Abutalebi, J., Paulesu, E., Brambati, S., Scifo, P., Cappa, S. F., et al. (2003). The role of age of acquisition and language usage in early, high-proficient bilinguals: An fMRI study during verbal fluency. *Human Brain Mapping*, 19, 170–182.
- Petersson, K. M., Reis, A., Askelof, S., Castro-Caldas, A., & Ingvar, M. (2000). Language processing modulated by literacy: A network analysis of verbal repetition in literate and illiterate subjects. *Journal of Cognitive Neuroscience*, 12, 364–382.
- Petitto, L. A., & Bellugi, U. (1988). Spatial cognition and brain organization: Clues from the acquisition of a language in space. In J. Stiles-Davies, U. Bellugi, & M. Kritchevsky (Eds.), *Spatial cognition: Brain bases and development* (pp. 299–341). Hillsdale: Erlbaum.
- Petitto, L. A., Katerelos, M., Levy, B. G., Gauna, K., Tetreault, K., & Ferraro, V. (2001). Bilingual signed and spoken language acquisition from birth: Implications for the mechanisms underlying early bilingual language acquisition. *Journal of Child Language*, 28, 453–496.
- Petitto, L. A., & Kovelman, I. (2003). The bilingual paradox: How signing-speaking bilingual children help us to resolve it and teach us about the brain's mechanisms underlying all language acquisition. *Learning Languages*, 5–19.
- Petitto, L. A., Zatorre, R. J., Gauna, K., Nikelski, E. J., Dostie, D., & Evans, A. C. (2000). Speech-like cerebral activity in profoundly deaf people processing signed languages: Implications for the neural basis of human language. *Proceedings of the National Academy of Sciences, U.S.A.*, 97, 13961–13966.
- Price, C. J. (2000). The anatomy of language: Contributions from functional neuroimaging. *Journal of Anatomy*, 197, 335–359.
- Price, C. J., Green, D. W., & von Studnitz, R. (1999). A functional imaging study of translation and language switching. *Brain*, 122, 2221–2235.
- Proverbio, A. M., Cok, B., & Zani, A. (2002). Electrophysiological measures of language processing in bilinguals. *Journal of Cognitive Neuroscience*, 14, 994–1017.



- Quaresima, V., Ferrari, M., van der Sluijs, M. C., Menssen, J., & Colier, W. N. (2002). Lateral frontal cortex oxygenation changes during translation and language switching revealed by non-invasive near-infrared multi-point measurements. *Brain Research Bulletin*, *59*, 235–243.
- Rodriguez-Fornells, A., Rotte, M., Heinze, H. J., Noesselt, T., & Munte, T. F. (2002). Brain potential and functional MRI evidence for how to handle two languages with one brain. *Nature*, *415*, 1026–1029.
- Rodriguez-Fornells, A., van der Lugt, A., Rotte, M., Britti, B., Heinze, H. J., & Munte, T. F. (2005). Second language interferes with word production in fluent bilinguals: Brain potential and functional imaging evidence. *Journal of Cognitive Neuroscience*, *17*, 422–433.
- Schellletter, C. (2000). Negation as a crosslinguistic structure in a German–English bilingual child. In S. Doepke (Ed.), *Cross-linguistic structures in simultaneous bilingualism*. Amsterdam: John Benjamins Publishing Company.
- Senghas, R. J. K., & Kegl, J. (1994). Social considerations in the emergence of Idioma de Signos Nicaraguense. *Signpost/International Sign Linguistics Quarterly*, *7*, 40–46.
- Stromswold, K., Caplan, D., Alpert, N., & Rauch, S. (1996). Localization of syntactic comprehension by positron emission tomography. *Brain and Language*, *52*, 452–473.
- Van Hell, J. G., & De Groot, A. M. B. (1998a). Conceptual representation in bilingual memory: Effects of concreteness and cognate status in word association. *Bilingualism: Language & Cognition*, *1*, 193–211.
- Van Hell, J. G., & De Groot, A. M. B. (1998b). Disentangling context availability and concreteness in lexical decision and word translation. *The Quarterly Journal of Experimental Psychology: Series A, Human Experimental Psychology*, *51A*, 41–63.
- Van Horn, J. D., Yanos, M., Schmitt, P. J., & Grafton, S. T. (2006). Alcohol-induced suppression of BOLD activity during goal-directed visuomotor performance. *Neuroimage*, *31*, 1209–1221.
- Vihman, M. M. (1985). Language differentiation by the bilingual infant. *Journal of Child Language*, *12*, 297–324.
- Volterra, V., & Taeschner, T. (1978). The acquisition and development of language by bilingual children. *Journal of Child Language*, *5*, 311–326.
- Wartenburger, I., Heekeren, R. H., Abutalebi, J., Cappa, F. S., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron*, *37*, 159–170.
- Weber-Fox, C. M., & Neville, H. J. (1996). Maturation constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience*, *8*, 231–256.
- Weber-Fox, C. M., & Neville, H. J. (2001). Sensitive periods differentiate processing of open- and closed-class words: An ERP study of bilinguals. *Journal of Speech, Language, and Hearing Research*, *44*, 1338–1353.
- Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex*, *11*, 946–995.