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Semantic processing in Spanish–English bilinguals with aphasia

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ABSTRACT

The present study was aimed at examining the effect of current language use/exposure on the neural representation of languages in Spanish–English stroke participants with aphasia using a semantic judgment task. Functional magnetic resonance imaging was performed on three participants with aphasia and three normal controls who had demonstrated a shift toward dominance in their second language (English). The behavioral and imaging results indicate that all participants processed their non-dominant native language (Spanish) differently compared to their dominant second language (English). Specifically, increased activation was observed in the left frontal cortex and anterior cingulate gyrus during the weaker native language processing. Further, in participants with aphasia, increased bilateral activation was observed during the weaker native language processing, indicating that decreased language usage/proficiency results in a distributed network of activation. The results of this study demonstrate that the neural substrates of language recovery in bilingual stroke patients are similar to regions engaged by normal bilinguals but include additional regions reflecting a compensatory network to subserve successful language processing.

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1. Introduction

The representation of languages in the brain of a bilingual speaker has been a subject of research for more than a century. Neuroimaging studies using positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have mainly focused on trying to elucidate if similar or distinct neural substrates subserve first language (L1) and second language (L2). Results from brain imaging and clinical studies indicate that bilinguals' language performance is influenced by a number of factors, including age of second language acquisition (AoA), proficiency level in either language, and language exposure and use (Abutalebi, 2008; Abutalebi, Cappa, & Perani, 2005; Indefrey, 2006; Sebastian, Laird, & Kiran, 2011). Behavioral and neuroimaging studies indicate that second language AoA has an impact on syntactic, morphological and phonological processing (e.g., Chambers & Cooke, 2009; Hernandez & Reyes, 2002), whereas proficiency in L2 has an impact on semantic processing (e.g., Abutalebi et al., 2005, 2008; Hernandez & Li, 2007; Stein et al., 2009; Tatsuno & Sakai, 2005). In addition to proficiency and AoA, the amount of daily language use also influences the brain regions activated by L2 (Perani et al., 2003).

Several recent neuroimaging studies investigating the neural substrates of lexical-semantic processing in bilinguals indicate that activation patterns during bilingual language processing tasks are driven by language proficiency (e.g., Abutalebi, 2008; Chee, Soon, & Lee, 2003; Hernandez & Li, 2007). Specifically, fMRI tasks engaging language processing in the two languages show that the less proficient language is associated with greater activation in the left inferior frontal gyrus (IFG) when compared to the more proficient language, indicating that the neurological system which underlies language appears to be engaged to a greater extent for the less proficient language (Abutalebi, 2008; Meschyan & Hernandez, 2006; Stein et al., 2009). In general, these studies have found that when the degree of proficiency for both languages in bilinguals is very high, a common language system comprising the left hemisphere language network appears to be responsible for the processing of both languages (e.g., Chee et al., 2003; Hasegawa, Carpenter, & Just, 2002; Hernandez, Hofmann, & Kotz, 2007; Klein, Watkins, Zatorre, & Milner, 2006; Perani et al., 1998). In bilinguals who are more proficient in one language than the other, however, a more extended network of activations is observed for the weaker language that includes brain regions related to speech motor and cognitive functions (e.g., Golestani et al., 2006; Kovelman, Baker, & Petitto, 2008; Luke, Liu, Wai, Wan, & Tan, 2002; Marian et al., 2007; Pillai et al., 2003; Tham et al., 2005; Yokoyama et al., 2006).

The study of language processing in brain-damaged individuals also provides relevant information to assess critical questions regarding bilingual language processing. Clinical studies have enhanced our knowledge regarding language representation in the bilingual brain. Language recovery patterns in bilingual stroke patients provide evidence for distinct and overlapping neuroanatomical representations of the different languages in the brain. For example, research on parallel recovery after stroke in bilinguals suggests that for many bilinguals and polyglots, the areas involved in processing language may be the same (Albert & Obler, 1978; Fabbro, 1999). Conversely, evidence suggesting that the neural substrates of the different languages may be segregated comes from those studies of aphasic patients who recover selectively in one language (e.g., Albert & Obler, 1978; Gomez-Tortosa, Martin, Gaviria, Charbel, & Ausman, 1995; Moretti et al., 2001).

Another approach that has been used to examine language representation in bilingual aphasia has been the study of brain-behavior patterns subsequent to lesions in core language processing regions, but these studies do not control for language proficiency or the nature of impairment (e.g., Berthier, Starkstein, Lylyk, & Leiguarda, 1990; Rapport, Tan, & Whitaker, 1983; Roux & Trémoulet, 2002). Additional evidence comes also from electrocortical stimulation in bilingual patients who undergo surgery (Ojemann & Whitaker, 1978), indicating that although L1 and L2 share some common areas, they also have independent brain regions. For example, Lucas, McKhann, and Ojemann (2004), compared electrical stimulation language mapping in 25 bilingual patients and 117 monolingual control patients and found that the stimulation of certain brain areas of epileptic patients interfered with L1 and L2 picture naming, while the stimulation of other areas disturbed L1 but not L2 naming and vice versa. Although these lines of research have provided interesting insights, the critical question regarding representation of languages in bilingual aphasia is still controversial.

Recent studies using fMRI have helped further our understanding of language representation in bilingual aphasia. For instance, Meinzer, Obleser, Flaisch, Eulitz, and Rockstroh (2007) examined neural

activation patterns in an early AoA, highly proficient German–French bilingual with chronic aphasia who showed selective recovery in German. This patient participated in a short-term intensive training program in German. Before training, better performance was noted in German compared to French and was accompanied by increased activation in the contralesional right temporal region. Post training, improved naming performance was accompanied by increased perilesional and contralesional activation for German, while the activation patterns for French remained unchanged. The results of this study demonstrate that language use and/or training-induced improvement in picture naming observed in the patient's first language was mediated by the reactivation of perilesional areas.

In another study, Abutalebi, Rosa, Tettamanti, Green, and Cappa (2009) investigated language representation in a late AoA, highly proficient Spanish–Italian bilingual with acute subcortical aphasia. The patient underwent fMRI scans before and after language treatment in L2 (Italian). The neural activation patterns were very similar for both L1 and L2 before the initiation of treatment, indicating that similar neural regions are recruited in a highly proficient bilingual individual. Following treatment, however, neural reorganization was present only for L2, the language treated in speech therapy. Extensive and significant foci of brain activity were observed in the prefrontal cortex and the anterior cingulate cortex (ACC) for L2 after treatment. This pattern was not observed for L1, in which no behavioral improvement took place. Thus, recovery of the treated language inhibited recovery on the untreated language. The authors suggested that improved performance in L2 after treatment was associated with increased connection strength of the network that mediated naming and language production. Further, the results also indicate that there was a shift in engagement of control regions from L1 to L2 and the improvement in L2 was attributed to increased connections with the prefrontal, left caudate and ACC.

Both of the above mentioned case studies indicate that premorbid language proficiency plays a role in determining the activation patterns in individuals with bilingual aphasia. The participants in both studies were highly proficient bilinguals prior to their stroke and had used both languages on a daily basis. It is unclear whether similar patterns will emerge if there is a difference in premorbid language proficiency and use. This issue is further compounded by the fact that early age of acquisition of a particular language does not guarantee greater proficiency in that language. Thus, it is possible that increasing use of L2 can lead to a dominance shift to the extent that L2 replaces L1 as the more proficient language. In fact, in an experiment examining translation times between L1 and L2, Heredia (1997) observed that despite being highly proficient in both languages, participants had experienced a shift in language dominance toward their L2, which led to a relatively weaker L1. This shift in language proficiency has been demonstrated in several other studies of Spanish–English bilinguals in the United States (Edmonds & Kiran, 2004; Heredia, 1997; Kiran & Lebel, 2007; Kohnert, 2002). Such a shift may have consequences for the neural representation of languages in a bilingual patient with aphasia even before he/she has experienced a stroke.

The present study was a preliminary attempt at examining the role of language use/proficiency in bilingual neural representations of language in three Spanish–English bilingual participants with aphasia. All participants were exposed to a predominantly English environment and were engaged in the use of English more than Spanish during their language learning years and consequently, were more proficient in English than Spanish in adulthood. We selected a task designed to examine the lexical-semantic system because semantic processing is more sensitive to language use/proficiency change than syntactic processing (e.g., Abutalebi, 2008; Hernandez & Li, 2007; Stein et al., 2009; Tatsuno & Sakai, 2005). In the present experiment, we utilized a semantic judgment task that has been used as a standard paradigm for assessing semantic processing in studies of monolingual and bilingual subjects (e.g., Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Chee, Hon, Lee, & Soon, 2001; Kurland et al., 2004; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill et al., 1998). Studies that have examined the neural correlates of semantic processing indicate that the left frontal and temporal lobes are usually active during different tasks requiring semantic retrieval and/or semantic selection (e.g., Binder, Desai, Graves, & Conant, 2009; Gabrieli et al., 1996; Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009; Thompson-Schill et al., 1998).

The following were the specific goals of the study. First, we examined the relationship between the activation data and behavioral responses in the three participants with aphasia relative to their controls. The objective was to examine if there was a difference in accuracy, reaction times and neural

activation patterns of English and Spanish between the patients and their controls. We hypothesized that if the patients demonstrated behavioral responses (in terms of accuracy/reaction times) and neural activation similar to their normal counterparts, then it could be surmised that the neurological damage to specific nodes in the language network in these participants with aphasia did not affect regions or processes engaged in bilingual lexical-semantic processing. Consequently, differences in activation patterns between the two languages, if present, could be attributed to language proficiency. Additionally, our previous meta-analytical review of fMRI studies in normal bilingual individuals (Sebastian et al., 2011) found that anterior cingulate cortex (ACC) and left prefrontal cortex (PFC) are engaged in low-proficient bilinguals relative to highly proficient bilinguals. We expect to find the same areas active in our low-proficient bilingual normal controls and participants with aphasia. If, on the other hand, participants with aphasia demonstrated similar behavior responses to controls but different patterns of activation, the findings would support the premise of perilesional/contralesional reorganization consistent with our previous results in monolingual aphasia that patients with good recovery of function recruit perilesional regions during language processing tasks (Sebastian & Kiran, 2011). Specifically, we observed that patients with large lesions and poor recovery of function recruit ipsilesional as well as contralateral regions during language processing tasks; an observation that has received support from a recent meta-analytical review of neuroimaging studies examining language recovery (Turkeltaub, Messing, Norise, & Hamilton, 2011).

Finally, if participants with aphasia differed from their age-matched controls in terms of both their behavioral responses and patterns of activation, it could be concluded that lesions affecting the language network are associated with impaired performance in the absence of functional reorganization. A similar conceptual logic has been applied to the preliminary understanding of the recovery of dysgraphia (Tsapkini, Vindiola, & Rapp, 2011) and serves as a good starting point for understanding the nature of language recovery in bilingual aphasia.

2. Methods

2.1. Participants

Three bilingual Spanish–English participants with aphasia were recruited for the experiment (age range 53–60, mean = 55.3). P1 suffered an ischemic stroke and P2 and P3 suffered cerebral hemorrhages. Strokes were generally in the distribution of the left middle cerebral artery and affected primarily posterior and/or anterior cortical areas (see Fig. 1). All participants were at least 12 months post onset (mean 33.6 MPO). All participants had concomitant medical problems such as heart disease, or diabetes; however, at the time of the participation they were medically and neurologically stable and at least wheelchair ambulatory.

Three age-matched normal bilingual participants were also recruited for the experiment (age range 41–69; mean = 57). The normal control participants had normal hearing and either normal or corrected to normal vision. Exclusionary criteria included neurological disorders such as stroke, transient ischemic attacks, Parkinson's disease, Alzheimer's disease, psychological illness, learning disability, seizures, and attention deficit disorders.

All participants were right handed as determined by the handedness and language inventory (Oldfield, 1971). All participants gave informed consent according to the University of Texas at Austin Human Subjects Protocol. Participants also completed screening forms to verify eligibility to participate in the scanner. The experiment was carried out in three sessions. The first session consisted of collecting the participant's medical history, language use history and administering language tests. The second session consisted of the behavioral experiment outside the scanner. This practice session was to ensure that the participants were able to perform the experimental task. The third session consisted of the fMRI experiment inside the scanner.

2.2. Language use and history profile

All participants received extensive background language assessments and a comprehensive language use questionnaire (Kiran, Pena, Bedore, & Sheng, 2010). This questionnaire obtained

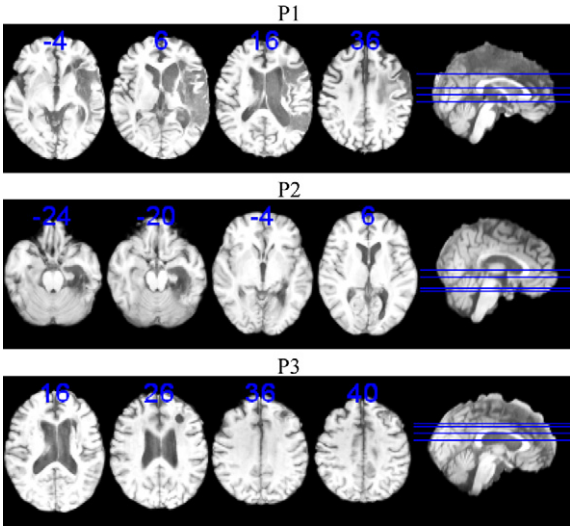

Fig. 1. T1 axial images for the three participants with aphasia in their native space. Images are in radiological orientation with the right side of the brain to the left and the left side to the right.

information about the period of age of language acquisition (AoA). Next, participants were required to self-rate their pre-stroke proficiency in each language in terms of their ability to speak and understand the language in formal and informal situations and read and write in each language. Again, an average proportion score in each language reflected participants' perception of their own language proficiency. Additionally, a proportion of language exposure in hearing, speaking and reading domains during the entire lifetime for each individual was obtained. A weighted average of the proportion of pre-stroke language exposure in the three domains was obtained for each language. Finally, participants estimated the time spent conversing in each language hour by hour during a typical weekday and typical weekend after the stroke occurred. A weighted average of this score reflected the proportion of post-stroke language exposure and use in the two languages. Participants were also asked to rate their family proficiency (estimates of parent/sibling proficiency) in each of the two languages. Finally, participants also filled out a detailed pre-stroke educational history form in which they were asked to provide the language of instruction in each language. The numerical results of this questionnaire are provided in Table 1 and explained in detail for each participant below.

2.2.1. Normal control participants

All normal control participants were exposed to Spanish from birth; normal control (NC) 1 was exposed to English at age 5; NC2 was exposed to English at age 6 and NC3 was exposed to English at age 3. NC1 was exposed to English 95% of the time and Spanish only 5% of the time, as compared to NC2 and NC3 who spent approximately 30% of the time conversing in Spanish and 70% of their time conversing in English. Information regarding lifetime exposure was not available for NC1, but for NC2 and NC3, lifetime exposure in English was approximately 65%, whereas lifetime exposure in Spanish was approximately 35%. Information regarding family proficiency was not available for NC1. Family proficiency in the two languages was rated at 100% for NC2. For NC3, family proficiency was rated at 50% for Spanish and 100% for English. Finally, with respect to language of instruction during education, NC1 stated that she used English in elementary, middle, high school and in college. NC2 reported using both languages in elementary school and middle school and English during high school. NC3 reported using both languages in elementary, middle and first year of high school.

2.2.2. Participants with aphasia

Patient 1 (P1) was exposed to English and Spanish from birth. Overall, P1 self-rated his pre-stroke proficiency in English at 100% and in Spanish at 40%. This difference matched his report of the hours

Table 1
(a) Participant demographic information, (b) language profile information.

(a)

Participant	Age/gender	Education	Site of lesion	MPO
NC1	41/F	Bachelor's degree	N/A	N/A
NC2	61/F	High school	N/A	N/A
NC3	69/M	9th grade	N/A	N/A
P1	60/M	Bachelor's degree	Left frontal including the motor cortex and part of the pars opercularis of Broca's area, SMA, temporal cortex and insula extending into the white matter	76
P2	53/F	Bachelor's degree	Left temporo-parietal region	12
P3	53/M	10th grade	Part of the left middle frontal cortex	13

(b)

Participant	Spa AoA	Eng AoA	Spa proficiency	Eng proficiency	Current exposure Spa	Current exposure Eng	Lifetime exposure Spa	Lifetime exposure Eng	Family proficiency in Spa	Family proficiency in Eng
NC1	0	5	83.67%	100%	5.04%	94.965%	N/A	N/A	N/A	N/A
NC2	0	6	77.14%	100%	31.09%	68.91%	34.15%	65.85%	100%	100%
NC3	0	3	100%	100%	31.09%	69.74%	34.22	65.78	50%	100%
P1	0	0	40%	100%	6%	94%	25%	75%	83%	83%
P2	0	0	74%	94%	46%	54%	39%	61%	100%	100%
P3	0	6	100%	100%	45%	55%	34%	66%	100%	67%

Note: for participants with aphasia Spanish/English proficiency is pre-stroke proficiency.

spent conversing in each language; he spent 94% of his time conversing in English. When examining his lifetime exposure to the two languages, exposure to Spanish was 25% and exposure to English was 75% during his 60 years. Family proficiencies in the two languages were rated at 83% each, indicating equal proficiencies in both languages. Finally, with respect to language of instruction during his education, P1 stated that he used English in elementary, middle, high school and in college.

Patient 2 (P2) was also exposed to both languages from birth. P2 self-rated her pre-stroke proficiency in English at 94% and in Spanish at 74%, but indicating lower proficiency in speaking English during formal situations and lower Spanish proficiency with respect to reading and writing skills. P2 spent most of her time in a bilingual conversational environment and her hours usage report indicated a slightly higher amount of time spent conversing in English (54%). When examining her lifetime exposure to the two languages, however, exposure to Spanish was 39%, whereas exposure to English was 61% during her 53 years. Family proficiency in the two languages was rated at 100% for both languages indicating that P2's family members were equally proficient in the two languages. With respect to language of instruction during her education, P2 reported using English in elementary school but both languages during middle school, high school and college.

Patient 3 (P3) was exposed to Spanish from birth and English from age 6. P3 self-rated his pre-stroke proficiency at 100% for both languages. Like P2, P3 spent most of his time in a bilingual conversational environment with a slightly higher amount of time spent conversing in English (55%). Also like P2, P3's lifetime exposure to the two languages indicated that exposure to Spanish was 34%, whereas exposure to English was 66% during his 53 years. Family proficiency in the two languages was rated at 100% for Spanish and 67% for English. P3's mother was only proficient in Spanish whereas his father and siblings were proficient in both languages. With respect to language of instruction during his education, P3 reported using both languages in elementary, middle and high school.

The results from the language use questionnaire indicate that all participants had stronger English proficiency relative to Spanish proficiency. Notably, NC1 was similar to P1 in the nature of the relative difference between current exposure to Spanish and English. Both individuals spent over 90% of their time conversing in English and only approximately 5% of their time in Spanish. NC2, NC3, P2 and P3 were similar in that they spent between one-third to one-half of their time conversing in Spanish while the remainder of their time was spent conversing in English.

2.3. Language tests

The language abilities of the participants with aphasia were examined using four tests. The *Western Aphasia Battery* (WAB; Kertesz, 1982) assessed aphasic symptoms and severity in English. Subtests from *Psycholinguistic Assessment of Language Processing in Aphasia* (PALPA; Kay, Lesser, & Coltheart, 1992) were administered in English to assess the semantic processing abilities. The *Boston Naming Test* (BNT; Kaplan, Goodglass, & Weintraub, 2001) examined naming abilities in English and Spanish. The *Bilingual Aphasia Test* (BNT; Paradis, 1989) examined language processing abilities in English and Spanish. Please see Table 2 for test scores.

Based on the results of the WAB tested in English, P1 presented with moderate Broca's aphasia characterized by nonfluent speech, impaired auditory comprehension, and impaired naming. P1's auditory comprehension skills were better than his naming and repetition skills. Both P2 and P3 presented with mild–moderate anomic aphasia characterized by fluent speech and impaired naming skills, with relatively preserved auditory comprehension and repetition skills. Results from selected subtests of the PALPA administered in English indicated that P1 and P3 scored perfectly or nearly perfectly on the PALPA spoken word picture matching (SWPM) and written word picture matching (WWPM) subtests. P2 scored nearly perfectly on the PALPA-SWPM, but had moderate difficulty on the PALPA-WWPM. All participants with aphasia demonstrated impairment in judging synonyms in written form. P1 and P3 also demonstrated impairment in judging synonyms in auditory form. However, P2 scored perfectly on the auditory synonym judgment task. These data indicate mild semantic impairments for P1 and P3. P2 presented with relatively preserved semantic processing ability in the auditory modality and moderate impairment in the written modality. Results of the BNT

Table 2
Test scores for participants with aphasia.

Tests	Max. scores	P1		P2		P3	
		English	Spanish	English	Spanish	English	Spanish
WAB-SP	20	12		17		13	
WAB-AC	10	6.2		8.6		8.9	
WAB-REP	10	2.4		9.6		8.6	
WAB-NAM	10	3.9		4.6		6.1	
WAB-AQ	100	61.4		79.7		73.2	
PALPA-SWPM	40	38		37		40	
PALPA-WWPM	40	38		***22***		36	
PALPA-WSJ	60	40		***36***		48	
PALPA-ASJ	60	46		60		46	
BNT	60	***7***	***0***	***7***	***6***	***32***	***4***
BAT-pointing	10	10	6	***4***	5	10	10
BAT-semicomplex commands	10	7	***4***	6	8	9	10
BAT-complex commands	20	***3***	***3***	14	12	13	7
BAT-semantic categories	5	4	3	4	5	***3***	***4***
BAT-semantic opposites	10	***0***	***0***	10	6	***2***	***3***
BAT-grammaticality judgment	10	6	***3***	10	8	8	6
BAT-semantic acceptability	10	7	7	10	7	10	10
BAT-reading comprehension words	10	10	***4***	6	***3***	10	7
BAT-reading comprehension sentences	10	8	5	6	***4***	7	8
		English to Spanish	Spanish to English	English to Spanish	Spanish to English	English to Spanish	Spanish to English
BAT-word recognition	5	5	4	5	5	5	5
BAT-translation of words	10	***0***	***1***	8	9	***3***	8
BAT-translation of sentences	18	***0***	***0***	18	16	12	15

Note: M – maximum score; WAB SP – WAB spontaneous speech; WAB AC – WAB auditory comprehension; WAB REP – WAB repetition; WAB NAM – WAB naming; WAB AQ – WAB aphasia quotient; PAPLA SWPM – PALPA spoken word to picture matching; PALPA-WWPM – PALPA written word to picture matching; PALPA WSJ – PALPA written synonym judgment; PALPA ASJ – PALPA auditory synonym judgment; BNT – Boston Naming Test; BAT – Bilingual Aphasia Test.

administered in both languages indicated severe word finding difficulty for P1 and P2 in English and Spanish. P3 had moderate word finding difficulty in English and severe word finding difficulty in Spanish.

The results of the BAT revealed that performance levels in English and Spanish were generally similar within each participant across languages. However, P1 was more severely impaired in both languages compared to P2 and P3. Further, based on the results of the BAT P1 was more impaired in Spanish than in English. For P1, accuracy was less than 50% on several subtests of the BAT in English and Spanish. The results of the BAT revealed that P2 and P3 demonstrated a more uniform deficit in both languages. P2 only scored less than 50% on one subtest in English (BAT-Pointing) and two subtests in Spanish (BAT-Reading comprehension words and sentences). P3 scored less than 50% on the BAT-Semantic opposites subtest in English and Spanish. P3 also scored less than 50% on the translation task (English to Spanish). In summary, it is clear that for all the three patients, the effect of brain damage seems to be relatively uniform for both languages. Specifically, the relative difference between the two languages persists even after stroke. P1 was more proficient in English prior to his stroke and his impairment level in English is less than Spanish. Both P2 and P3 were relatively proficient in both languages and impairment levels in English and Spanish were similar after the stroke.

2.4. Task and design

The experiment consisted of a semantic judgment task in both Spanish and English. The stimuli for the task were selected from a previous norming study (Edmonds & Kiran, 2004). The semantic judgment task employed in this study is similar to that utilized in Chee et al. (2001) and Kurland et al. (2004); participants were presented with word triplets and required to decide which two of the three words were semantically related. During this task, participants were expected to visually analyze the words, compare two choices with the target in terms of semantic relatedness and subsequently select the choice that best matched with the target. The control condition consisted of a size judgment task. During this task, participants were presented with symbol string triplets and required to decide which two of the three symbol strings were closer in terms of size. Symbol strings consisted of 10 different symbols that were selected randomly to form 4–7 symbol strings. The length of the symbol strings varied because the lengths of the stimuli for the semantic and size judgment task were matched. One of the symbol strings was 8% smaller than the target and the other was 16% larger than the target. There were 48 word triplets in each language. The control condition consisted of 96 symbol triplets. The control condition was kept simple in order to maximize the opportunity of correct responses in participants with aphasia. The control task was assumed to have required several of the same task components in visual processing, as well as in response selection, as was required during the experimental task. In this way, it was thought to be a tight comparison for the purpose of fMRI analysis as the response demands were similar (judge which two items are related). It was, therefore, hypothesized that subtraction of the control condition from the experimental condition would identify regions involved in semantic processing.

The stimuli were presented using an event-related design with jittered interstimulus intervals (ISIs). The control condition was presented during the ISI. Each stimulus was presented for 5 s and the ISIs varied from 4–6 s. The experiment was divided into two runs and each run consisted of 24 word triplets in each language and 48 symbol triplets. All stimuli were concrete nouns and controlled for frequency of occurrence (Frances & Kucera, 1982; Juilland & Chang-Rodriguez, 1964). All words were 1–3 syllables in length. The average length of Spanish words was significantly longer (1.9 (SD = 0.52) syllables) than the English words (1.59 (SD = 0.60) syllables) (t (190) = −4.05, $p < 0.01$). Nevertheless, words used in this study were representative of the typical word length in Spanish and English.

2.5. Procedure

Magnetic resonance images were acquired on a 3 Tesla GE MRI scanner. The stimuli were presented with E-Prime, (Psychology Software Tools, Inc.) using an in vivo system that presents images on a screen fitted to the head coil in the MRI scanner. Corrective optical lenses were used when needed to correct visual acuity. Participants responded by pressing the middle finger of their left hand to choose

the word option on the left of the screen and the index finger to choose the word option on the right. Participants wore earplugs to reduce the scanner noise.

Once subjects were positioned in the scanner, the magnet was shimmed to achieve maximum homogeneity. Scout images (4 s) were obtained to determine the proper angle for subsequent structural and fMRI data acquisitions. This was followed one high-resolution T1-SPGR scan lasting 5 min and 44 s (128 1 mm sagittal slices, FOV 240×240 mm, flip angle = 20, bandwidth = 31.25, phase encoding = A-P, TR = 9.5 ms, TE = 6.1 ms). Blood-oxygen-level-dependent (BOLD)-sensitive functional images were collected using a gradient echo-planar pulse sequence (TR = 2000 ms, TE = 35 ms, 64×64 matrix, 24×24 cm FOV, flip angle 90°, 31 oblique slices covering the whole brain, 3 mm thick, 0.3 mm interslice gap). Before all the runs began, a baseline fixation condition for 8 s was presented to ensure that the scans had reached the equilibrium.

3. Data analysis

3.1. Behavioral

The data were analyzed in terms of accuracy and reaction times recorded from the button press response in E-Prime. Only correct responses were entered into the reaction time and fMRI data analyses, as previous fMRI studies have found bilateral activation for incorrect responses in participants with aphasia (Postman-Caucheteux et al., 2010). All behavioral analyses were performed using Statistica (StatSoft, Tulsa, OK).

3.2. Imaging

Each participant's (participants with aphasia and normal controls) data was analyzed individually and reported as a case series as the variability in the lesion site/sizes preclude combined analyses of participants. All fMRI data were analyzed using the Oxford Centre for Functional MRI of the Brain (FMRIB) — FMRIB's software library (FSL) version 5.9 (Smith et al., 2004; Woolrich et al., 2009). Image preprocessing was performed to remove non-brain tissues and correct for image intensity fluctuations and RF inhomogeneities. The following pre-statistics processing were applied: motion correction (Jenkinson, Bannister, Brady, & Smith, 2002); non-brain removal (Smith, 2002); spatial smoothing using a Gaussian kernel of FWHM 5 mm; mean-based intensity normalization of all volumes by the same factor; highpass temporal filtering (Gaussian-weighted LSF straight line fitting, with sigma = 60.0 s). After preprocessing, statistical analyses were performed at the individual level (for both control subjects and participants with aphasia) within FSL (FEAT, FMRI Expert Analysis Tool). The task timing was convolved with the standard gamma variate function implemented in FSL (lag, 6 s; width, 3 s), and the fMRI signal was then linearly modeled on a voxel-by-voxel basis using a general linear model (GLM) approach, with local autocorrelation correction (Woolrich, Ripley, Brady, & Smith, 2001). The three explanatory variables of interest were English semantic, Spanish semantic and size judgment. Contrasts examined differences in activation between (1) semantic decision in English vs. size, (2) semantic decision in Spanish vs. size, (3) semantic decision in English vs. Spanish, and (4) semantic decisions in Spanish vs. English.

Registration of participants' fMRI image to the MNI standard space was carried out using a linear image registration tool included in FSL. Functional images were first aligned to the T1-weighted SPGR, and then the T1-SPGR to the standard MNI Avg152, T1 $2 \times 2 \times 2$ mm. All transformations were carried out by using 12 degrees of freedom affine transforms (Jenkinson & Smith, 2001). For participants with aphasia, the cost function masking method of normalization was employed (Brett, Leff, Rorden, & Ashburner, 2001), in which a hand-drawn stroke mask, derived from the T1 MRI scan, prevents the normalization algorithm from interpreting the infarct's edge as part of the brain surface. T1-weighted images form each patient was also normalized into MNI space using the cost function masking method found in FLIRT (Jenkinson & Smith, 2001). Higher level analysis (analysis across runs for the same subject) was carried out using fixed effects. Z (Gaussianised T/F) statistic images were thresholded using clusters determined by $Z > 2.3$ and a (corrected) cluster significance threshold of $p = 0.05$ (Worsley, 2001).

3.3. Regions of interest (ROI) analysis

ROI analyses were performed in order to examine the patterns of activation for L1 and L2 in regions that are typically sensitive to language proficiency changes (Chee et al., 2001; Sebastian et al., 2011; Stein et al., 2009). The following regions were included: left inferior frontal gyrus (LIFG), left middle frontal gyrus (LMFG), and cingulate gyrus (CG). Homologous areas on the right side were chosen as ROIs in the right hemisphere. The LIFG ROI included only the pars triangularis region, as the pars opercularis region was lesioned in P1. The mean intensity of signal change associated with Spanish and English semantic judgments in these regions of interest was extracted. The anatomical mask for each ROI was created using fslmaths (part of FSL) and the Harvard–Oxford cortical structural atlas was used as a guide for defining anatomical landmarks. The mean activation within each region associated with each task for each participant was obtained using the Featquery tool, which is part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). We have successfully implemented these procedures in one recent study to examine task related activation in stroke participants with aphasia (Sebastian & Kiran, 2011).

4. Results

4.1. Behavioral data

The mean reaction time and mean accuracy rate for each individual participant is shown in Fig. 2. Normal control participants were significantly faster during English semantic judgment (Mean = 1731.2 ms) compared to Spanish semantic judgment (Mean = 2132 ms) ($Z = 11.69$; $p = 0.00$). Further, normal control participants were significantly more accurate during English semantic judgment (Mean = 92.2% accuracy) compared to Spanish semantic judgment (Mean = 90% accuracy) ($Z = 14.0$; $p = 0.00$). Participants with aphasia were significantly faster during English semantic judgment (Mean = 2417.2 ms) compared to Spanish semantic judgment (Mean = 2830.3 ms) ($Z = 11.22$; $p = 0.00$). Also, participants with aphasia were significantly more accurate during English semantic judgment (Mean = 71% accuracy) compared to Spanish semantic judgment (Mean = 64.3% accuracy) ($Z = 15.19$; $p = 0.00$). Fig. 2 shows that the mean effect was representative of the individual trends in the three normal controls and the three patients.

4.2. Imaging data

The list of activation coordinates (in MNI standard space) is provided in Tables 3 and 4 and activation maps (Z statistics) for each contrast are shown in Figs. 3 and 4. For the normal control participants, in general, English semantic judgment, when compared to size judgment, showed activation in the left frontal and temporal regions. Spanish semantic judgment, when compared to size judgment, activated the bilateral frontal regions, left temporal and cingulate regions. English semantic judgment, when contrasted directly with Spanish semantic judgment did not show any significant activation in any of the three normal controls. Spanish semantic judgment, when contrasted directly with English semantic judgment activated the left inferior frontal gyrus for NC1 and NC2. Additional activity was observed in the right inferior frontal gyrus for NC1 and right superior temporal gyrus for NC2. For NC3 activation was observed in the right inferior frontal gyrus and right middle temporal gyrus. Thus, all three normal controls showed greater activation for Spanish relative to English in the right hemisphere.

The neural activation patterns for participants with aphasia were very similar to that observed in the normal control participants. Specifically, more regions were activated during Spanish semantic processing compared to English semantic processing. For P1, who sustained a large lesion involving the left frontal and left temporal lobe (see Fig. 1), English semantic judgment compared to size judgment activated perilesional frontal and temporal regions. The regions included the left superior temporal gyrus, left post central gyrus, left supramarginal gyrus and left sub insular lobe. Spanish semantic judgment compared to size judgment activated both left hemisphere and right hemisphere regions. This included the bilateral superior frontal gyrus, left middle frontal gyrus, and bilateral cingulate gyrus. English semantic judgment, when contrasted directly with Spanish semantic judgment

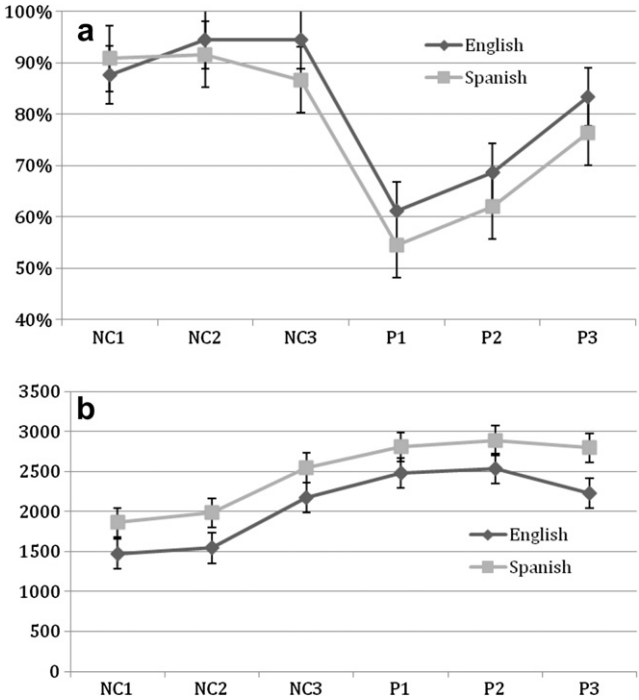

Fig. 2. (a) Mean accuracy rate and (b) mean reaction time for normal control participants and participants with aphasia.

activated the left supramarginal gyrus, left superior temporal gyrus and left inferior frontal gyrus (pars triangularis). Spanish semantic judgment, when contrasted directly with English semantic judgment activated the bilateral cingulate and left frontal pole.

For P2, whose lesion involved the left temporo-parietal region, English semantic judgment compared to size judgment activated the left inferior frontal gyrus, left lateral occipital cortex, and right middle temporal gyrus. Spanish semantic judgment compared to size judgment activated both left hemisphere and right hemisphere regions; including the left inferior frontal gyrus, bilateral middle frontal gyrus, right angular gyrus, right posterior cingulate gyrus and right superior frontal gyrus. English semantic judgment, when contrasted directly with Spanish semantic judgment did not show any significant activation. Spanish semantic judgment, when contrasted directly with English semantic judgment activated the bilateral middle frontal gyrus, left middle temporal gyrus, right angular gyrus and bilateral cingulate gyrus.

For P3, whose lesion involved part of the left middle frontal gyrus, English semantic judgment compared to size judgment activated the left inferior frontal gyrus and left middle frontal gyrus. Spanish semantic judgment compared to size judgment activated the left inferior frontal gyrus, left middle frontal gyrus, left temporal gyrus, left angular gyrus and left cingulate gyrus. English semantic judgment, when contrasted directly with Spanish semantic judgment activated the left inferior and middle frontal gyrus. Spanish semantic judgment, when contrasted directly with English semantic judgment activated left middle frontal gyrus, right inferior frontal gyrus, right temporal gyrus and right cingulate gyrus.

4.3. Regions of interest (ROI) analysis

The mean percent BOLD signal change for the three normal control participants and participants with aphasia are shown in Figs. 5 and 6. For the three normal control participants, greater percent BOLD signal change was observed in the LIFG and LMFG for Spanish semantic judgment relative to English

Table 3
Mean activation coordinates and significance (*Z* statistics) for normal control participants.

Region	English vs. size				Spanish vs. size				English vs. Spanish				Spanish vs. English			
	Z	*x*	*y*	*z*	*Z*	*x*	*y*	*z*	*Z*	*x*	*y*	*z*	*Z*	*x*	*y*	*z*
NC1																
Left hemisphere																
Inferior frontal gyrus, BA 45/44	4.0	−50	16	18	6.6	−54	20	14					3.0	−54	20	10
Middle frontal gyrus, BA 46	4.3	−36	6	58	6.3	−42	26	24								
Superior temporal gyrus, BA 22	4.4	−62	−32	0	4.3	−54	−30	2								
Middle temporal gyrus, BA 21	3.9	−52	−46	0	4.0	−56	−38	2								
Supramarginal gyrus, BA 40	4.3	−52	−44	32	6.0	−48	−50	12								
Middle occipital gyrus, BA 18					4.3	−32	72	18					3.8	−34	−74	26
Right hemisphere																
Inferior frontal gyrus, BA 44/45					4.0	44	32	14					3.2	48	18	26
Middle frontal gyrus, BA 46					5.0	48	34	24								
Middle occipital gyrus, BA 18					4.2	42	70	24					3.0	42	74	26
NC2																
Left hemisphere																
Inferior frontal gyrus, BA 45/44	4.4	−46	16	18	4.0	−50	24	14								
Middle frontal gyrus, BA 46	5.9	−30	20	40	2.7	−30	38	34					2.8	−44	20	28
Superior frontal gyrus, BA 8	4.2	−14	56	18	4.1	−12	46	34								
Precentral gyrus, BA 4					4.7	−43	−8	34					3.7	−42	−6	34
Postcentral gyrus, BA 3					4.9	−51	−6	24					2.9	−50	−8	24
Superior temporal gyrus, BA 22	6.0	−68	−34	4	6.9	−64	32	4								
Middle temporal gyrus, BA 21	5.8	−60	−40	4	6.8	−62	42	0								
Supramarginal gyrus, BA 40					5.9	−54	−44	10								
Middle occipital gyrus, BA 18					5.1	−42	−80	16								
Posterior cingulate					6.4	−4	−8	34								
Right hemisphere																
Superior temporal gyrus, BA 22					6.4	60	−14	−6					2.9	54	−28	2
Middle temporal gyrus, BA 21					6.2	56	22	10								
Supramarginal gyrus, BA 40					2.9	62	−42	16								
Anterior cingulate, BA 24					4.5	4	−12	32								
NC3																
Left hemisphere																
Inferior frontal gyrus, BA 45/44	6.3	−42	28	10	6.7	−52	24	14								
Postcentral gyrus, BA 3	7.0	−58	−16	24	4.9	−66	−16	14								
Middle frontal gyrus, BA 46	5.5	−38	20	46	6.1	−38	18	39								
Superior frontal gyrus, BA 8	3.2	−8	32	44												
Middle temporal gyrus, BA 21																
Superior occipital gyrus, BA 19	4.5	−32	−74	46												
Inferior occipital gyrus, BA 17					4.2	−42	−74	−18								
Anterior cingulate, BA 24					3.5	−4	−9	33								
Right hemisphere																
Inferior frontal gyrus, BA 45/44					5.6	46	30	12					4.8	56	18	4
Middle frontal gyrus, BA 46					5.9	32	16	30								
Precentral gyrus, BA 4													4.7	60	2	38
Postcentral gyrus, BA 3	4.0	54	−10	24	4.7	56	−20	20								
Middle temporal gyrus, BA 21					6.5	−52	−32	−8					4	56	−24	4

semantic judgment. Greater BOLD signal change was also observed in the RMFG for Spanish semantic judgment for NC1 and NC3 and cingulate gyrus for both NC2 and NC3. The percent BOLD signal change for participants with aphasia was similar to that observed in the normal control participants. All three participants showed greater percent BOLD signal change in LIFG, LMFG and cingulate gyrus for Spanish relative to English. All three patients also showed positive BOLD signal changes in the RMFG for Spanish but negative BOLD signal in this region for English processing, a finding not noted in the three normal controls.

Table 4
Mean activation coordinates and significance (*Z* statistics) for participants with aphasia.

Region	English vs. size				Spanish vs. size				English vs. Spanish				Spanish vs. English			
	Z	*x*	*y*	*z*	*Z*	*x*	*y*	*z*	*Z*	*x*	*y*	*z*	*Z*	*x*	*y*	*z*
P1																
Left hemisphere																
Inferior frontal gyrus, BA 45	2.5	−62	12	5					3.1	−60	12	4				
Middle frontal gyrus, BA 46					3.9	−38	24	40								
Superior frontal gyrus, BA 8					3.7	−24	40	28								
Superior temporal gyrus, BA 22	4.2	−34	10	−34					2.5	−58	8	−4				
Sub insular lobe, BA 13	2.8	−46	−22	18												
Postcentral gyrus, BA 3	2.5	−40	−26	34												
Supramarginal gyrus, BA 40	2.5	−50	−28	24					2.8	−60	−40	22				
Cingulate gyrus, BA 24					2.7	−6	38	22					3.6	−2	48	−8
Superior frontal gyrus, BA 8					3.3	20	40	44								
Right hemisphere																
Frontal pole													4.6	32	38	−14
Cingulate gyrus, BA 24					2.5	12	46	6					3.5	8	38	0
P2																
Left hemisphere																
Inferior frontal gyrus, BA 44	2.5	−48	16	8	2.3	−46	18	7								
Precentral gyrus, BA 4																
Middle frontal gyrus, BA 46					2.6	−30	22	38					2.5	64	−20	−10
Sub insular lobe, BA 13																
Middle temporal gyrus, BA 21													3.5	−62	−50	2
Lateral occipital gyrus, BA 17	2.8	−22	−86	26												
Cingulate gyrus, BA 24													3.4	−8	50	2
Right hemisphere																
Middle frontal gyrus, BA 46					2.5	44	16	38					4.0	40	16	32
Superior frontal gyrus, BA 8					3.0	20	56	20								
Angular gyrus, BA 39					2.7	48	−50	36					3.6	46	48	28
Cingulate gyrus, BA 24					2.4	14	−54	38					2.4	16	48	2
P3																
Left hemisphere																
Inferior frontal gyrus, BA 45	4.2	−48	38	4	2.5	−42	32	10								
Inferior frontal gyrus, BA 44	2.6	−44	24	20	3.3	−52	20	10	3.5	−48	28	−2				
Middle frontal gyrus, BA 46	3.6	−44	40	8	2.9	50	24	24					2.7	−52	−28	−6
Precentral gyrus, BA 4													2.6	−44	4	22
Middle temporal gyrus, BA 21					2.7	−66	−42	4								
Angular gyrus, BA 39					2.5	−48	−60	24								
Cingulate gyrus, BA 24					3.4	−6	24	42								
Right hemisphere																
Inferior frontal gyrus, BA 45													2.6	50	30	4
Frontal pole													3.0	32	48	34
Superior temporal gyrus, BA 22													2.6	52	26	0
Cingulate gyrus, BA 24													2.4	2	28	34

5. Discussion

This study was aimed at examining the effect of current language use/proficiency on the neural representation of semantic processing in Spanish–English bilinguals with aphasia. In this study, we examined neural activation patterns in three normal control participants and three chronic participants with aphasia. Even though all six participants were native Spanish speakers, all participants' English usage was greater than their Spanish usage. Notably, both NC1 and P1 showed a remarkable difference in their relative use and proficiency between English and Spanish, whereas NC2, NC3, P2 and P3 were only slightly more proficient in English than Spanish. The results of the behavioral and imaging

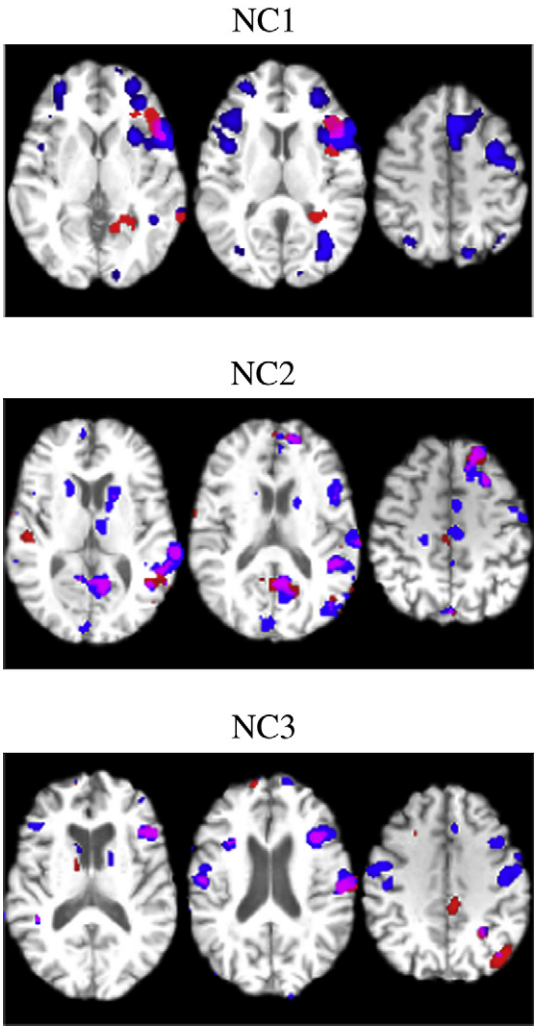

Fig. 3. Activation maps for the normal control participants. 'Red' represents English > control, 'Blue' represents Spanish > control and 'Purple' represents overlap in activation. Statistical maps are thresholded by using clusters determined by $Z > 2.3$ and a (corrected) cluster significance threshold of $p = 0.05$. Images are in radiological orientation with the right side the brain to the left and the left side to the right. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

experiment suggest that behaviorally, all participants responded less accurately and more slowly in Spanish than in English. Correspondingly, patterns of neural activation for all participants reflected greater activation for Spanish relative to English. The results therefore support our first hypothesis proposed in the introduction; that both participants with aphasia and their controls demonstrate differences in processing English and Spanish stimuli during a lexical-semantic processing task and that this difference is reflective of a disparity in language use and proficiency (greater proficiency in English than Spanish). The results, however, also partially support our second hypothesis, in that there are some smaller but important differences between the patients and their controls in the face of generally similar behavioral and neural responses. Each of these results will be discussed in greater detail.

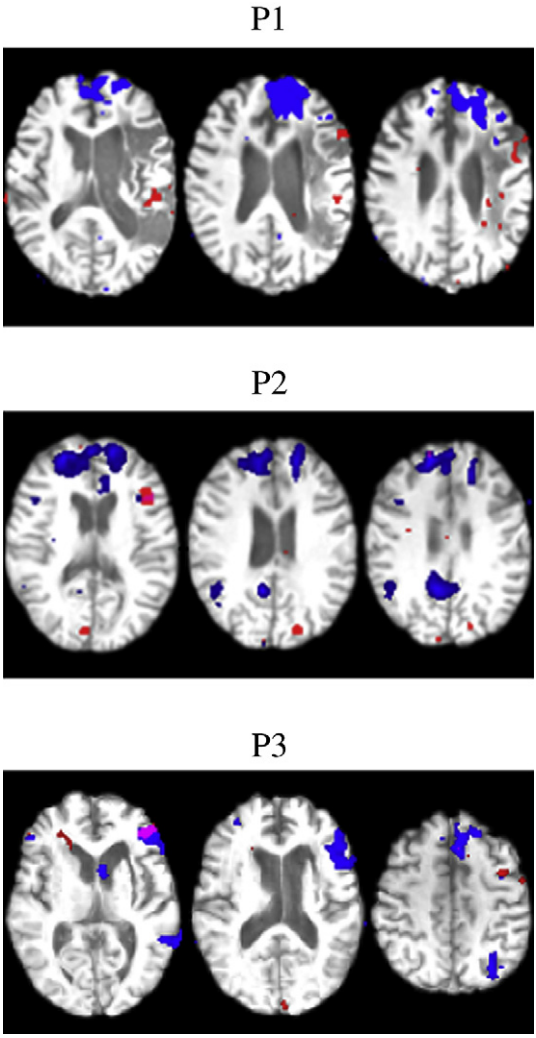

Fig. 4. Activation maps for participants with aphasia. 'Red' represents English > control, 'Blue' represents Spanish > control and 'Purple' represents overlap in activation. Statistical maps are thresholded by using clusters determined by $Z > 2.3$ and a (corrected) cluster significance threshold of $p = 0.05$. Images are in radiological orientation with the right side the brain to the left and the left side to the rights. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Let us first examine the activation patterns in the normal controls. It should be noted that all the three participants demonstrated relatively lower accuracy and slower reaction times for Spanish compared to English stimuli on the semantic judgment task. NC1 was slightly more accurate in Spanish compared to English. This could be attributed to a difference in language use and proficiency between English and Spanish. The results of the whole brain and ROI analyses revealed that all the three normal control participants showed robust left-sided activation in the left frontal and/or temporal cortex during the English semantic judgment task. The highest level of BOLD signal change in English was observed in the left IFG (pars opercularis (BA 44) and pars triangularis (BA 45)), and extending into the prefrontal cortex. Left IFG activation, predominantly within BA 45 and BA 44, has been associated with monolingual lexical-semantic processing in numerous functional imaging studies (e.g., Badre &

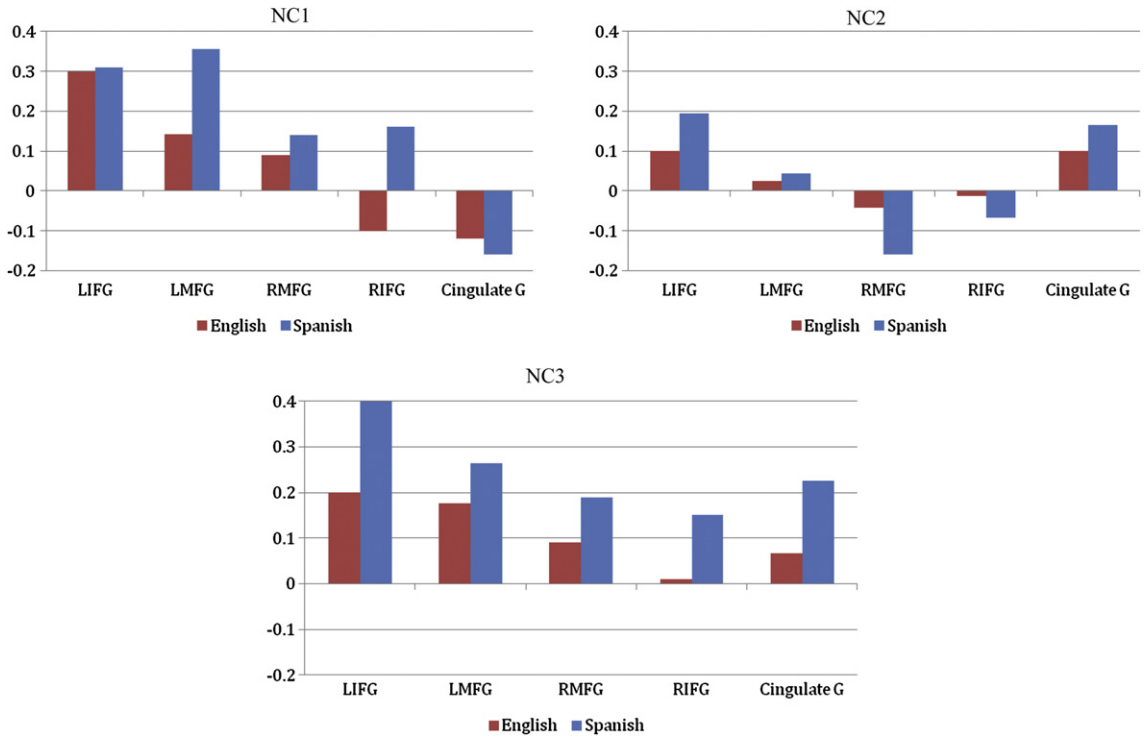

Fig. 5. Mean % BOLD signal change for the three normal control participants.

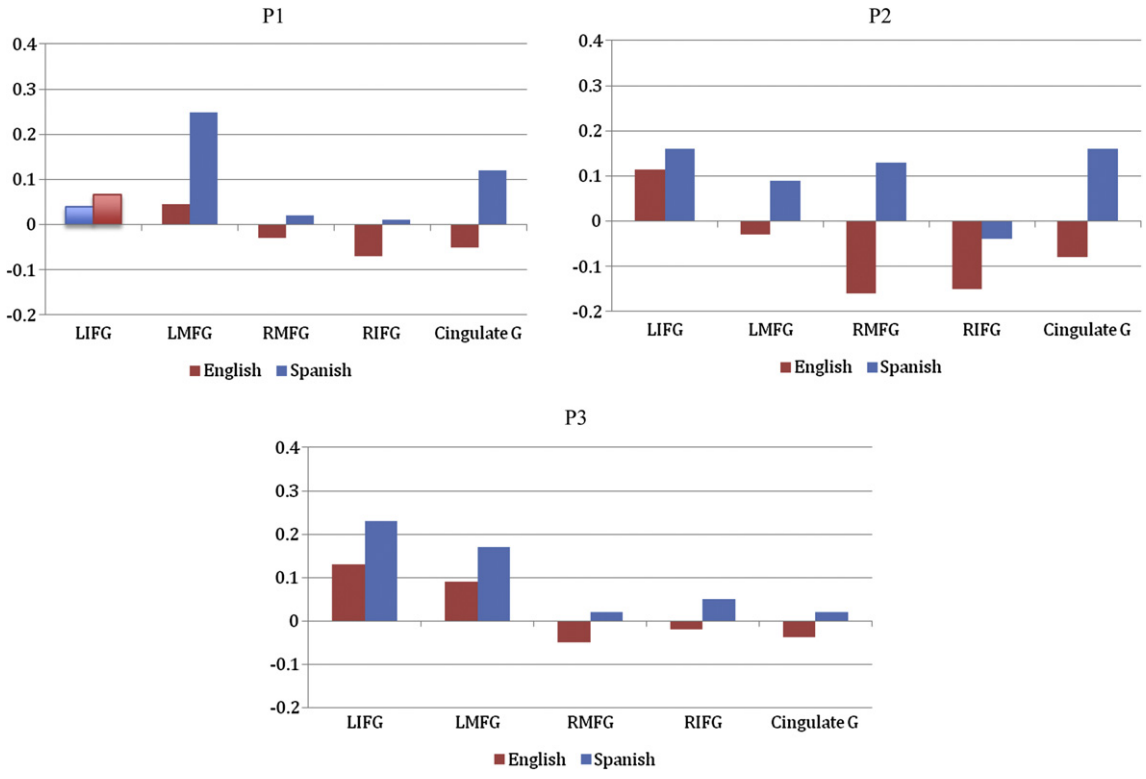

Fig. 6. Mean % BOLD signal change for the three participants with aphasia.

Wagner, 2002; Fiez, 1997; Kapur et al., 1994; Thompson-Schill et al., 1997). Similar regions were also activated in the left frontal and temporal cortex during the Spanish semantic judgment task. Although there was an overlap in the left frontal and temporal regions during Spanish and English semantic processing, the activated volumes were larger in the frontal and temporal regions for the Spanish semantic judgment task compared to the English semantic judgment task for all the three normal controls.

At first glance the activation patterns observed in Spanish for the normal controls appear to be similar; however, a closer inspection of the individual data for the normal control participants revealed increased variability in the activation patterns for Spanish semantic judgment task. This variability observed in the normal control participants could be attributed to varying language proficiency in Spanish. The three main regions that showed difference in activation between Spanish and English are the cingulate cortex, the prefrontal cortex and right hemisphere regions. NC1 did not show any cingulate activation during Spanish semantic judgment, whereas NC2 and NC3 showed activity in the cingulate region. Imaging studies have reported activity in the anterior cingulate cortex during tasks that engage selective attention, response selection, monitoring of conflicting responses, error detection, and initiation of action (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998; Fu et al., 2002; Kiehl, Liddle, & Hopfinger, 2000; MacDonald, Cohen, Stenger, & Carter, 2000). In the present study, while making semantic judgments in Spanish, there might be an intrusion from the frequently used language (English). This may induce a degree of response conflict and place a demand on response selection, leading to activation of the anterior cingulate cortex. Thus, the recruitment of this area during semantic judgment task in Spanish is most probably secondary to response conflict and increased attentional demand. This premise is also supported by several behavioral studies that show that the nontarget language is activated and that cross-language effects appear even in situations and tasks that are purely monolingual. For example, in unbalanced bilinguals, cross-language effects of L2 on L1 were found in a purely L1 context (Van Hell & Dijkstra, 2002; Van Wijnendaele & Brysbaert, 2002).

The left middle frontal gyrus, a part of the prefrontal cortex, was consistently activated in all the three normal controls. Increased BOLD signal change was noted in the LMFG for all the three normal control for Spanish semantic judgment compared to English semantic judgment. The prefrontal cortex is considered to be a mechanism that facilitates the processing of task-relevant representations even in the presence of prepotent irrelevant ones (Dehaene & Changeux, 1991; Desimone & Duncan, 1995; Miller & Cohen, 2001). In the present study, increased activation observed in the left prefrontal cortex during Spanish semantic judgment might be attributed to the need to block the stronger language (English) in order to process words in the weaker language (Spanish). This is also in line with evidence from previous studies that found anatomical differences, mainly within the left prefrontal cortex, for low-proficient bilinguals in studies that used lexical decision and semantic judgment tasks in bilinguals (for example, lexical decision: Illes et al., 1999; Pillai et al., 2003; semantic judgment: Chee et al., 2001; Ruschemeyer, Fiebach, Kempe, & Friederici, 2005; Ruschemeyer, Zysset, & Friederici, 2006; Wartenburger et al., 2003).

Increased activity was also observed in the right fronto-temporal regions for the normal control participants during Spanish semantic processing. Both NC1 and NC3 activated the RIFG and RMFG during Spanish semantic processing compared to size judgment. NC2 did not activate any right frontal regions during Spanish semantic judgment. Increased activation was observed in the right temporo-parietal regions for NC2 during Spanish semantic processing. Increased activation in the right hemisphere regions has been reported in low-proficient bilinguals to compensate for reduced language proficiency (Luke et al., 2002; Meschyan & Hernandez, 2006; Yokoyama et al., 2006). To summarize these results, processing Spanish may have produced greater activation in the anterior cingulate, prefrontal cortex and right fronto-temporal regions because the search for semantic relatedness between the words was influenced by the fact that Spanish was the less frequently used language. This increased processing load may place greater demand on available resources during semantic judgments. This interpretation is supported by the significantly longer reaction times for Spanish semantic processing compared to English semantic processing.

Now let us examine the results from the participants with aphasia. The pattern of brain activity in participants with aphasia closely resembled the pattern of activity observed in the normal control

participants, supporting our first hypothesis that normal controls and participants with aphasia will demonstrate similar pattern of neural and behavior responses. For participants with aphasia the language use pattern and proficiency as well as the behavioral response patterns were similar to their controls. Like their corresponding normal controls, P1 showed a greater difference in proficiency between English (L2) and Spanish (L1); however, P2 and P3 were not as unbalanced as P1, although they were both more proficient in English. In terms of their language usage, P1's Spanish usage was limited to only a few hours every week, whereas P2 and P3 used more Spanish on a daily basis. In terms of the behavioral data, overall, lower accuracy rates and longer reaction times were noted for Spanish semantic judgments compared to English semantic judgments. First, all three participants with aphasia showed activation in the LIFG and/or the LMFG for both English semantic judgment vs. size and Spanish semantic judgment vs. size. Further, when Spanish semantic judgment was directly contrasted with English semantic judgment, increased neural activity was observed in all participants with aphasia in the bilateral cingulate gyrus and left middle frontal gyrus (P2 and P3). For P3, perilesional activation was observed in the left middle frontal gyrus. Additional regions were also activated in a bilateral fronto-temporal network (Spanish vs. English; See Table 4).

While the above results mostly confirm our first hypothesis (similar patterns of behavioral and neural responses between participants with aphasia and controls), there are some important differences in the patient results that partially support our second hypothesis. First, all the three participants had lower accuracies and longer reaction times on the task than their normal controls. This finding is to be expected as a consequence of brain damage. At the neural level, one interesting difference emerged between participants with aphasia and normal controls when English semantic judgment was directly compared to Spanish semantic judgment. Increased activity was observed in the perilesional regions for P1 (IFG, STG, and SMG) and P3 (IFG). No difference in activity was observed for P2 (English vs. Spanish; See Table 4). Similarly, no difference in activation was observed for all normal controls when English semantic judgment was directly contrasted with Spanish semantic judgment. The increased perilesional activity observed for P1 and P3 are likely related to the lesion in regions that are typically associated with lexical-semantic processing. Therefore, perilesional response observed during English processing, the frequently used language may reflect successful compensatory function for P1 and P3.

Additionally, subtle differences emerged for each patient, in accordance with differences in the site and size of lesion. P1 sustained a large lesion involving the left frontal and temporal regions, and correspondingly, limited activation was observed within the spared left hemisphere tissue for this individual. Despite a large lesion, P1 is using the spared tissue to its fullest, as evidenced by the lack of engagement of the right hemisphere homolog during the stronger L2 (English) processing. For Spanish semantic processing some right hemisphere activations were noted in the cingulate region and frontal pole. It should be noted that the left inferior frontal gyrus, pars triangularis was spared in P1 and this region has been associated with lexical-semantic processing (for review see Binder et al., 2009). Robust perilesional frontal activation (BA 45) was noted for P1 during English semantic processing. However, this spared region was not recruited during the weaker Spanish processing indicating that the perilesional tissue was not being efficiently used during the weaker language processing. Previous studies in monolingual patients with aphasia found that improved language functions were related to the activation of perilesional regions (Heiss et al., 1997; Postman-Caucheteux et al., 2010; Sebastian & Kiran, 2011). The lack of activation of the perilesional tissue during Spanish processing might be related to decreased language use over time limiting the participation of the perilesional tissue for functional recovery. This likely results in recruiting a more distributed network of regions during Spanish processing. Thus, the recruitment of perilesional regions during English processing might be related to extensive usage of English over a period of time resulting in a more circumscribed network of activation for the stronger language. This result is also in line with two recent case studies in bilingual aphasia that found enhanced recovery of language functions in the treated language was related to the reintegration of perilesional regions (e.g., Abutalebi et al., 2009; Meinzer et al., 2007).

P2's lesion was much smaller than P1's lesion, encompassing part of the left temporo-parietal cortex. Therefore, activated volumes and regions in the left hemisphere were larger for P2 compared to P1. With regard to the site of lesion, the left inferior frontal gyrus (pars opercularis and pars triangularis) was not lesioned in P2. Therefore, robust activation was observed in the LIFG during English and Spanish semantic judgments. However, no perilesional posterior activation was noted for both L1

and L2. ROI analysis demonstrated increased BOLD signal change in the LIFG for Spanish semantic processing compared to English semantic processing. Interestingly, negative BOLD signal changes were noted in the four ROI (LMFG, RMFG, RIFG, and cingulate gyrus) for English semantic judgments, whereas negative BOLD signal change was only noted in the RMFG for Spanish semantic judgment. The lack of recruitment of all the ROI regions except the LIFG for English semantic judgment indicates that extensive usage of a language over a period of time results in a more circumscribed network of activation.

P3's lesion was the smallest, encompassing part of the left middle frontal gyrus. Similar to P2, activated volumes and regions in the left hemisphere were larger for P3 compared to P1. Since the left inferior frontal gyrus was spared in P3, there was robust activation in this region for both English and Spanish semantic judgment. Perilesional middle frontal gyrus activation was also observed for both L1 and L2. Left posterior activation was only noted for Spanish semantic judgment. Similar to P2, ROI analysis revealed deactivation in RIFG, RMFG and cingulate gyrus for English semantic judgment. Although positive activation was noted in the RIFG, RMFG and cingulate gyrus for Spanish semantic judgment, the % signal change was smaller compared to P1 and P2. This could be attributed to increased proficiency level in Spanish for P3 resulting in more circumscribed network of activation for Spanish.

Notably, all participants with aphasia, irrespective of the site or size of lesion, showed increased activation in the right hemisphere and cingulate regions during Spanish semantic processing. In studies examining monolingual stroke individuals with aphasia, increased activity in the right hemisphere and cingulate region has usually been linked to a less favorable outcome in most studies and seems to be related to error processing (Postman-Caucheteux et al., 2010) or recovery level (Cao, Vikingstad, George, Johnson, & Welch, 1999; Dombovy, 2009; Heiss & Thiel, 2006; Winhuisen et al., 2007). In our study, increased activity was observed in the right hemisphere and cingulate region during the processing of a Spanish, the less proficient (pre-stroke) and more difficult language post-stroke. It should be noted that only correct responses were included in the fMRI analysis and therefore, greater activation in the right hemisphere is not because of greater demands placed on processing more difficult information but likely due to greater demands placed on processing a less proficient language effectively.

To summarize, the results from the patient data indicate that similar to the normal controls there is increased variability in activation patterns for Spanish semantic judgment compared to English semantic judgment, most likely due to variability in language proficiency and use. This difference, however, cannot be attributed to differences in site and size of lesion, as this should induce variability in both English and Spanish processing. All the three patients were proficient in English but had varying degrees of proficiency in Spanish resulting in varying in activation pattern in Spanish. The increased variability also indicates that less proficient bilinguals engage greater cognitive resources when processing the less used/less proficient language. The results are in line with previous studies that have found weaker language processing to elicit more activation and more individual variation in activation patterns than stronger language processing (Ruschemeyer et al., 2005; Vingerhoets et al., 2003).

6. Summary and conclusion

The results of this study indicate that as is the case with the non-brain-damaged bilingual individuals (for review see, Abutalebi, 2008; Sebastian et al., 2011), the relative level of L2 proficiency and use play an important role in bilingual aphasia. Further, the results also indicate that the patterns of activation in participants with aphasia are driven more by proficiency rather than site and size of lesion. For bilingual patients with similar language impairment, the less used language resulted in greater activations, not only in regions traditionally involved in language processing but also in regions known to sustain the 'cognitive control system', such as the prefrontal cortex and the anterior cingulate cortex. Thus, the left prefrontal and anterior cingulate activity may constitute an important neural signature of language dominance in the bilingual brain.

The results further confirm the premise that greater proficiency in a language recruits a more focal core language network, whereas lower usage/proficiency in language recruits a more distributed

network of regions. This observation of an inverse relationship between proficiency and activation has also been reported in studies of motor learning (Ma et al., 2010; Xiong et al., 2009), indicating that proficiency induces efficiency. This premise is also consistent with our previous work in bilingual aphasia rehabilitation (Edmonds & Kiran, 2006) that has shown that training the less proficient language (i.e., a more diffuse network) in stroke patients results in cross-language transfer to the more proficient language, whereas training the proficient language (i.e., a highly specialized network) does not result in cross-language transfer to the weaker language. Therefore, it could be argued that training the less proficient language network may intrinsically strengthen the dense stronger language network because of the overlapping nodes in the two networks. Further, these results also indicate that it is very important to assess bilingual patients' proficiency and language use pattern in L1 and L2 prior to the initiation of language treatment.

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