Neuropsychologia ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Neural signatures of second language learning and control

James Bartolotti [a,*], Kailyn Bradley [b], Arturo E. Hernandez [b], Viorica Marian [a]

[a] Northwestern University, Department of Communication Sciences and Disorders, 2240 Campus Drive, Evanston, IL 60208, USA
[b] University of Houston, Department of Psychology, 3695 Cullen Boulevard, Houston, TX 77204, USA

ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form
1 April 2016
Accepted 7 April 2016

Keywords:
Language learning
Crosslinguistic competition
Lexical processing
Inhibitory control
fMRI

ABSTRACT

Experience with multiple languages has unique effects on cortical structure and information processing. Differences in gray matter density and patterns of cortical activation are observed in lifelong bilinguals compared to monolinguals as a result of their experience managing interference across languages. Monolinguals who acquire a second language later in life begin to encounter the same type of linguistic interference as bilinguals, but with a different pre-existing language architecture. The current study used functional magnetic resonance imaging to explore the beginning stages of second language acquisition and cross-linguistic interference in monolingual adults. We found that after English monolinguals learned novel Spanish vocabulary, English and Spanish auditory words led to distinct patterns of cortical activation, with greater recruitment of posterior parietal regions in response to English words and of left hippocampus in response to Spanish words. In addition, cross-linguistic interference from English influenced processing of newly-learned Spanish words, decreasing hippocampus activity. Results suggest that monolinguals may rely on different memory systems to process a newly-learned second language, and that the second language system is sensitive to native language interference.

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1. Introduction

Experience-dependent plasticity refers to the lifelong process of neural specialization as a result of practice in a domain. Different types of visual (Gauthier et al., 2000; Kwok et al., 2011), spatial (Maguire et al., 2000), and auditory (Krizman et al., 2014; Sluming et al., 2002) experiences have lasting effects on informational processing and cortical structure. Knowledge of multiple languages is one such form of experience with far-reaching outcomes that has been examined in a number of studies (see Hernandez, 2013). For example, in bilinguals, changes in gray matter volume have been directly related to both age of acquisition and proficiency in a second language (Mechelli et al., 2004), demonstrating that cortical changes are sensitive to different types and amounts of language exposure.

Neural plasticity from second language experience extends beyond language processing to affect core cognitive processes, and these changes also lead to differences in cortical structure. Bilinguals are uniquely challenged to prevent interference from the non-target language during both language comprehension (Chambers and Cooke, 2009; Ju and Luce, 2004; Marian and Spivey, 2003a; Spivey and Marian, 1999) and production (Colomé and Miozzo, 2010; Green, 1998) in the target language. Bilinguals' lifelong experience controlling access to two languages is thought to heighten their executive functioning abilities (Bialystok, 2015; for an opposing view see Hilchey and Klein, 2011). This increase in ability is reflected in changes in the prefrontal cortex during attentional control tasks compared to monolinguals (Bialystok et al., 2005; Luk et al., 2010), and in recruitment of the frontal cortex during language processing (Abutalebi, 2008; Hernandez et al., 2001; Marian et al., 2014).

Critical to our understanding of bilingual language processing in adults is how changes in language experience correspond to changes in neural structure and processing. Beginning second language learners process two languages differently than fluent bilinguals because of learners' asymmetry in proficiency (Kroll and Bogulski, 2013; Kroll and Stewart, 1994). This asymmetry also affects how language learners control interference between languages (Bartolotti and Marian, 2012; Costa and Santesteban, 2004). By studying patterns of second language acquisition, it is possible to assess the trajectory of experience-related changes in neurological processing. The effects of second language acquisition on the brain have been explored in a wide body of research covering multiple timescales and types of information processing. Long-term training paradigms have identified the processes that contribute to storage and use of a novel language, whereas short-term training studies demonstrate learning mechanisms at early stages, which involves transfer of word knowledge from short-term memory to long-term lexical storage.

* Corresponding author.
E-mail address: j-bartolotti@u.northwestern.edu (J. Bartolotti).

http://dx.doi.org/10.1016/j.neuropsychologia.2016.04.007
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Specifically, long-term training experiments show that extended study of a second language results in experience-related changes in gray matter density in frontal regions and the hippocampus. Adults undergoing intensive study of a foreign language over a three month period had increases in gray matter volume in the hippocampus, left inferior frontal gyrus, middle frontal gyrus, and superior temporal gyrus (Mårtensson et al., 2012). The magnitude of these changes correlated with proficiency gains over a three-month period, suggesting that gray matter increases were related to learning success. Similarly, college students tested before and after five months studying a language abroad showed greater gray matter density in left inferior frontal gyrus and the left anterior temporal lobe, two areas implicated in lexical access and semantic integration (Stein et al., 2012). Second language training in a controlled laboratory setting has also been shown to affect neural structure. Native Japanese speakers with limited English experience who engaged in a 16 week series of English vocabulary training sessions showed increased gray and white matter density in right inferior frontal gyrus, and this increase was positively correlated with their proficiency gains (Hosoda et al., 2013).

Compared to the long-term changes observed primarily in frontal cortical regions, short-term training effects are seen in additional areas involved in learning and memory. The hippocampus in particular is a potential marker for the onset of second language learning due to its utility in the formation of memories for diverse components of language. Learning paired associates in another language, for example pictures of objects with novel words, is related to changes in hippocampus activation (Breitenstein et al., 2005; Henke et al., 1999). Transcranial stimulation of areas of cortex that have direct connections to the hippocampus can further improve novel vocabulary learning through these same mechanisms (Flöel et al., 2008). The role of the hippocampus is not limited to vocabulary, but extends to early stages of grammar learning. As grammatical knowledge in a second language shifts from a collection of semantic facts to procedural rules, an associated shift is observed from initial hippocampal activity to distributed cortical activation (Helmstaedter et al., 1997; Opitz and Friederici, 2003; Wagner et al., 1998).

Models of second language acquisition explicitly mark the transition from initial hippocampal storage to later integration with the existing lexicon in a more distributed fashion (Davis and Gaskell, 2009). Behavioral evidence for this consolidation phase comes from vocabulary training studies. After learning novel words that are neighbors of existing English words (e.g., *cathedruke*, which differs in the final phoneme from *cathedral*), competition from the novel word is observed only after a period of intervening sleep, during which time the novel word can be integrated into the lexicon and cortically distributed (Dumay and Gaskell, 2007). The learned words continue to affect native language processing for several months (Tamminen and Gaskell, 2008), consistent with the timecourses involved in hippocampal and cortically-distributed memory systems.

Whereas competition from the novel language during native language processing is dependent on lexical integration of the newly-learned words, the converse case may be observed at earlier stages. In bilinguals, relative proficiency can modulate the amount of competition, with the dominant language leading to more competition during processing of the less dominant language (Blumenfeld and Marian, 2007). In second language learners, for whom there is a large asymmetry between their two languages, native language competition should occur at early stages of learning. This type of competition is less well examined, although some behavioral studies have shown that native English words can compete with newly-learned vocabulary in an artificial language immediately post-training (Bartolotti et al., 2013; Bartolotti and Marian, 2012).

The current study was designed to investigate language learning and control in monolingual adults and had two aims. *The first aim* was to compare neural signatures for auditory processing of native language words and of newly-learned words in a second language. *The second aim* was to determine the extent to which native language knowledge interferes with recently-learned second language vocabulary. We taught English monolinguals 40 spoken Spanish words paired with concrete pictures (e.g., *muñeca*, meaning *doll*) through brief paired-associate learning. Then, in separate English and Spanish language blocks, participants identified the picture that matched a spoken target in a four-alternative forced choice task. Comparing performance in English and Spanish language trials allowed us to detect differences in how first and second languages are represented at early stages of learning. Because of the short timescale over which training occurs, we predict strong activation of the hippocampus during Spanish word processing. Spanish language trials were divided into Competitor and No-competitor trials, based on the properties of other pictures in the visual display. In Competitor trials, the English name of one of the non-target pictures overlapped with the Spanish spoken target (e.g., target *muñeca* and English competitor *moon*). This critical comparison was included to examine the processes used by monolinguals to control cross-linguistic competition at early stages of second language learning.

2. Materials and methods

2.1. Participants

Eighteen English monolinguals (12 females, mean age=22.28 years, SD=3.69) participated in the current study. All participants were university students and were right-handed, healthy adults with no history of neurological or psychiatric illness. Because language learning and phonological competition are affected by cognitive factors including memory span and inhibitory skill (Gass et al., 2013; Mackey and Sachs, 2012), we measured participants' executive functioning (colored shapes version of the Simon task, Simon and Rudell, 1967), academic achievement (grade point average), phonological memory, and sequence memory (non-word repetition and digit span subtests, respectively, from the *Comprehensive Test of Phonological Processing*, Wagner et al., 1999).

2.2. Materials

Participants learned 40 Spanish words that referred to concrete, imageable objects. Twenty of the Spanish words shared phonological onset with an English competitor word (e.g., the Spanish word *sobre*, meaning envelope, overlaps with the English competitor *soap*). Each of the twenty stimuli sets included a Spanish target (e.g. *sobre*, meaning 'envelope'), an English competitor (e.g. *soap*), a matched control word (e.g. *meat*, which does not overlap with *sobre* or its translation *envelope*), and two unrelated words (e.g. *fin* and *paintbrush*); a full list is provided in Appendix. The five words within a set were used to construct two matched trials with four objects each: a competitor trial including the target, competitor, and both unrelated items (e.g., *envelope/sobre*, *soap*, *fin*, and *paintbrush*); and a control trial in which the competitor was replaced with the control item (e.g., *envelope/sobre*, *meat*, *fin*, and *paintbrush*). All stimuli in a set were matched on word frequency (SUBTLEXUS, Brysbaert and New, 2009), orthographic and phonological neighborhood size (CLEARPOND, Marian et al., 2012), and concreteness, familiarity, and imageability (MRC Psycholinguistic Database, Coltheart, 1981) (all $ps > .05$). Items in a set were visually represented by black and white line drawings obtained from the International Picture Naming Project (IPNP) database (Bates et al., 2003) or from Google Images. IPNP pictures were selected for high naming consistency, and pictures from Google Images were independently normed by 20 English monolinguals on Amazon Mechanical Turk (https://www.mturk.com). Across all items, picture naming reliability from the IPNP or Turk ratings was 92% (SD=10.8). Naming reliability for the critical Competitor condition ranged from 75% to 100%.

2.3. Procedure

Testing took place in two sessions for each participant. In the first session, the participant gave informed consent in accordance with the Institutional Review Boards of Northwestern University and the University of Houston. Then the participant was screened for claustrophobia, health conditions, and presence of metal in the body, and completed the Simon task and the Comprehensive Test of

Please cite this article as: Bartolotti, J., et al., Neural signatures of second language learning and control. Neuropsychologia (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.04.007

Phonological Processing (CTOPP).

In the Simon task, participants viewed red and green circles that appeared on the left, right, or center of a computer screen and selected a response based on the item's color, while ignoring its location. The instructions were to press a button on the left side of the keyboard if the circle was red, or a button on the right if the circle was green (color to side mappings counterbalanced across participants). In congruent trials, the stimulus and response were on the same side (e.g., a red circle on the left side of the screen), and in incongruent trials, the stimulus and response were on opposite sides (e.g., a red circle on the right side of the screen). In neutral trials, the circle appeared in the center. There were 180 trials (60 each of Congruent, Incongruent, and Neutral) presented in a pseudorandom order; the inter-trial interval varied between two, four, six, or eight seconds. The Simon effect was calculated by subtracting response time on Congruent trials from response time on Incongruent trials. A small Simon effect indicates better ability to ignore the inconsistent location cue, and high executive function.

Participants completed two subtests of the CTOPP: Nonword repetition and Digit span. The Nonword repetition test indexes phonological memory. In each trial, the participant listens to a nonsense word and repeats it out loud. The nonwords increase in length from 3 to 15 phonemes. The phonological memory score is an age-normed value computed from the number of nonwords repeated correctly. The Digit span test indexes sequence memory. The participant listens to a sequence of digits and repeats it in the same order; the sequences increase in length from two up to eight digits. Sequence memory is an age-normed value computed from the number of correct sequences.

In the second session, the participant was familiarized with the fMRI scanner and was given sound dampening headphones to reduce scanner noise, a squeeze ball to signal the technician in case of an emergency, and a button box to make responses during the task. The visual display was projected onto a mirrored screen that yielded a visual angle of 13–15 degrees, and the participant received auditory input over the headphones. Each participant first completed an English phonological competition task in the scanner while images were acquired. Then participants were taught Spanish vocabulary and were tested on recognition of the newly-learned words while they remained in the scanner. No images were acquired during training. Immediately after training, participants completed the Spanish phonological competition task, where images were again acquired. After completing the scanning session, participants were taken out of the scanner and completed one additional test to assess their Spanish vocabulary spoken word production.

2.3.1. Phonological competition task

The English and Spanish runs each included 80 four-alternative forced-choice word recognition trials using the visual world paradigm. In each trial, four pictures were simultaneously presented on the search display, one in each corner. After 500 ms, the target word was played over headphones. The search display remained on the screen for 2500 ms, and participants were instructed to indicate the location of the target using one of the four buttons on their handheld button box. Each response quadrant was assigned to a single response button. Target location was counterbalanced across trials, and trials were presented in a pseudo-randomized order that was fixed between participants, with the constraint that no image was seen more than once in three consecutive trials. Stimuli were presented in an event-related design using E-Prime 2.0 software (Psychology Software Tools, Pittsburg, PA) with an inter-trial interval ranging from 4.5 to 11.7 s

The 80 trials in the Spanish task were broken down into 20 competitor trials, 20 matched no-competitor trials, and 40 filler trials. Competitor trials included a Spanish target word and an English competitor that overlapped phonologically with the onset of the target (e.g., Spanish target *sobre*, meaning 'envelope,' and English competitor *soap*), as well as two unrelated items that shared no phonological overlap with any other items in the set (e.g., *paintbrush* and *fin*). The no-competitor trials were derived from the competitor trials by replacing the overlapping picture (e.g., *soap*) with a control item whose name did not overlap with the target or with any other items in the display (e.g., *meat*, which does not overlap with *sobre* or its English translation). All filler trials contained a Spanish target and three unrelated pictures (e.g., target *cuenco*, meaning 'bowl,' and unrelated items *needle*, *shower*, and *gum*). Each of the 40 Spanish targets was used in two trials, with one of the unrelated items changed between trials to maintain the same procedure as the competitor sets. These filler trials were included to prevent participants from becoming aware of the phonological overlap present in competitor trials.

The 80 trials in the English task included 20 no-competitor trials and 60 filler trials. The no-competitor trials were designed to match the Spanish no-competitor trials in lexical characteristics (frequency, neighborhood size, concreteness, familiarity, and imageability, all $ps > .05$) and were used to compare Spanish and English language activation. In each of these English comparison trials, an English target was paired with three phonologically unrelated items (e.g., target *magnet*, and unrelated items *witch*, *pencil*, and *corn*).

2.3.2. Spanish word learning

Between the English and Spanish competition tasks, participants remained in the same position in the scanner and completed the Spanish vocabulary training task (images were not acquired during the training period). Participants were trained on 40 Spanish words repeated in three different trials, for a total of 120 training trials. In each trial, four pictures were displayed in the four corners of the screen. The target picture was outlined in a red box and at the same time the Spanish name of the target was played auditorily. Each display was presented for three seconds, and automatically advanced to the next trial after a one second inter-stimulus interval. Participants were instructed to learn the words as they would be tested on them later. The three unrelated pictures in a display were competitors and fillers from the upcoming Spanish phonological competition task in order to reduce novelty effects. Target pictures were paired with different unrelated pictures during the training and phonological competition tasks. The participant remained in the scanner following training and completed the Spanish vocabulary recognition assessment and then the Spanish phonological competition task.

2.3.3. Vocabulary learning assessments

To assess Spanish vocabulary learning, recognition and production tests were administered. The recognition task was given immediately after training while participants were still in the scanner (no images were acquired). The task contained 40 trials. In each trial, four learned pictures appeared in the four corners of the display, and the Spanish target was played simultaneously with display onset. Each of the 40 learned words appeared as a target once and as an unrelated picture in the display three times. The trial ended either when the participant made a response, or after five seconds had elapsed, triggering a time-out. The following trial then began after a 500 ms inter-trial interval.

The Spanish production task was performed with the participant seated at a computer outside the scanner after the scanning session was completed. The production task also contained 40 trials. Participants viewed each of the 40 pictures one at a time on a computer screen and produced the Spanish name for each picture aloud; responses were recorded and scored for accuracy.

2.4. Neuroimaging parameters

Functional neuroimaging data were collected using a 3.0 Tesla head-only Siemens Magnetom Allegra magnetic imager. Anatomical images were acquired using high-resolution T_1-weighted anatomical scans with an MPRAGE sequence at a voxel size of $1.0 \times 1.0 \times 1.0$ mm, TR=1200 ms, TE=2.93 ms, reconstructed into 192 slices. Functional images were acquired in 34 axial slices parallel to the AC-PC line with an interleaved descending gradient recalled echo-planar (EPI) imaging sequence with a voxel size of $3.4 \times 3.4 \times 4.0$ mm, TR=2700 ms, and TE=28 ms.

2.5. Data analysis

2.5.1. fMRI data processing and analysis

Functional images for each subject were analyzed using SPM8 software (Wellcome Trust Centre for Neuroimaging, London, UK). During preprocessing, images were realigned for motion correction, resliced, and slice time corrected. The functional images were coregistered to align the mean functional image with the structural image, segmented, and normalized to a standard MNI (Montreal Neurological Institute) template. Functional data were spatially smoothed using an 8 mm full-width half maximum (FWHM) Gaussian kernel to compensate for any additional variability after normalization.

In first-level processing, the stimulus onsets for each condition (20 competitor trials, 20 no-competitor trials, 40 filler trials), including correct and incorrect trials, were implicitly modeled against rest in each participant using a General Linear Model (GLM). Motion estimates from preprocessing were entered as covariates of no interest at the first-level to further control for motion artifacts, a method validated for use in event-related fMRI paradigms (Johnstone et al., 2006). At the second-level, each of the comparisons of interest was analyzed using paired *t*-tests including each participant's contrast images from first-level processing. This included Spanish no-competitor compared to English no-competitor (Language activation analysis) and Spanish competitor compared to Spanish no-competitor (Cross-linguistic competition analysis). Monte Carlo simulations with AFNI's ALPHASIM program were performed to correct for multiple comparisons. All comparisons used a voxel-level threshold of $p < .01$ and a minimum cluster size of 442 contiguous voxels, for a cluster-level significance of $p < .05$. Activation coordinates (MNI) were provided by SPM, and anatomical labeling was obtained from the Talaraich atlas after conversion to Talaraich coordinates (Lancaster et al., 1997, 2000). Whole brain activation in English and in Spanish are reported in Appendix. Spanish activation includes all 60 trials with no phonological competition (20 no-competitor trials and 40 filler trials) implicitly modeled against rest, and English activation includes 60 trials matched for lexical characteristics (frequency, neighborhood size, concreteness, familiarity, and imageability, all $ps > .05$) with the Spanish trials. Each comparison was analyzed using a one-sample *t*-test including each participant's contrast images from the first-level processing, and used a voxel-level threshold of $p < .05$, FWE corrected.

Please cite this article as: Bartolotti, J., et al., Neural signatures of second language learning and control. Neuropsychologia (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.04.007

2.5.2. Behavioral data analysis

The effects of individual ability and word characteristics on Spanish word learning were assessed in the recognition and production tasks using mixed effect general linear models (GLM). Accuracy data were fit using a binomial distribution, and reaction time data were fit using a normal distribution after log transformation. For each dependent measure (recognition accuracy, recognition response time on correct trials, and production accuracy), a base model was constructed that included only random effects of participant and item. Then a comparison model added fixed effects of individuals' phonological and sequence memory (nonword repetition and digit span performance), academic achievement (grade point average), and inhibitory control (Simon effect score), as well as fixed effects of words' length in phonemes, Spanish log frequency (SUBTLEX-ESP, Cuetos et al., 2011, to control for possibility of prior word exposure), and English-similarity (mean English phoneme probability, CLEARPOND, Marian et al., 2012). All predictors were z-transformed. Improvement to model fit was assessed using a chi-square analysis on the −2LogLikelihood change in fit, after which the effects of individual parameters were assessed.

The effect of phonological competition on performance in the Spanish fMRI task was also assessed using mixed effect general linear models. Accuracy data were fit with a binomial distribution, and response time data were fit with a normal distribution after log transformation. Base models for accuracy and RT were constructed that included only random effects of participant and item, and were compared to models that included a fixed effect of condition (competitor trial, unrelated trial). Change in model fit was assessed using a chi-square analysis on −2LogLikelihood change in fit.

3. Results

3.1. Spanish vocabulary learning

Participants correctly identified 67.9% (SD=15.5%) of the words in the recognition task, scoring significantly better than the chance level of 25%, ($t(17)=11.74$, $p<.001$). A mixed effect GLM was used to assess the effects of individual factors on accuracy. Adding participant and item predictors significantly improved model fit compared to the base model, $\Delta LL=75.92$, $X^2(7)=151.84$, $p<.001$ (Table 1A). Phonological memory was positively associated with accuracy (*Estimate*=98.69, *SE*=41.98, $z=2.35$, $p<.05$), whereas sequence memory was negatively associated with performance (*Estimate*=−46.37, *SE*=23.13, $z=-2.01$, $p<.05$). No other predictors (English phoneme probability, Spanish frequency, word length, inhibitory control, or academic achievement) were significantly associated with accuracy.

Table 1
Parameter estimates for mixed effect models of Spanish vocabulary learning.

Parameter	Estimate	SE	*z* Score
(*A*) *Recognition accuracy*			
Intercept	66.19	29.75	2.23*
Mean English phoneme probability	−23.32	22.76	−1.03
Spanish frequency	38.12	23.57	1.62
Length	36.88	29.8	1.24
Phonological memory	98.69	41.98	2.35*
Sequence memory	−46.37	23.13	−2.01*
Inhibitory control	−23.31	21.39	−1.09
Academic achievement	−25.4	23.43	−1.08
(*B*) *Recognition RT*			
Intercept	3.35	0.021	161.35***
Mean English phoneme probability	0.019	0.009	2.18*
Spanish frequency	−0.012	0.009	−1.27
Length	0.001	0.011	0.11
Phonological memory	−0.008	0.038	−0.21
Sequence memory	0.019	0.021	0.88
Inhibitory control	0.011	0.019	0.55
Academic achievement	-0.021	0.021	−0.96
(*C*) *Production accuracy*			
Intercept	−124.153	31.152	−3.985***
Mean English phoneme probability	−30.7	23.835	−1.288
Spanish frequency	69.516	24.744	2.809**
Length	−02.908	30.208	−0.096
Phonological memory	74.544	42.056	1.773
Sequence memory	−14.427	23.25	−0.621
Inhibitory control	−47.79	20.959	−2.28*
Academic achievement	53.411	23.868	2.238*

SE=Standard error.
* $p<.05$.
** $p<.01$.
*** $p<.001$.

Average response time on the recognition task in correct trials was 2276 ms (SD=460.78). A mixed effect GLM was used to assess the effects of individual factors on RT. Adding the predictors significantly improved fit compared to the base model , $\Delta LL=902.7$, $X^2(7)=1805.4$, $p<.001$ (Table 1B). Words' English similarity affected RT (*Estimate*=0.019, *SE*=0.009, $z=2.18$, $p<.05$), with it taking longer to identify the matching picture for the more English-like words. A one SD change in English similarity (e.g., a change in mean phoneme probability equal to the increase from *bisagra* to *bolsa*) corresponded to approximately a 96 ms increase in RT. No other predictors (Spanish frequency, word length, phonological memory, sequence memory, inhibitory control, or academic achievement) significantly affected recognition RT.

Production accuracy was 34.4% (SD=19.1%). A mixed effect GLM was used to assess the effects of individual factors on accuracy, and model fit compared to the base model improved after adding the predictors, $\Delta LL=172.74$, $X^2(7)=172.74$, $p<.001$ (Table 1C). Better inhibitory control (i.e., a smaller Simon effect) was associated with increased accuracy, (*Estimate*=−47.79, *SE*=20.96, $z=-2.28$, $p<.05$), as was academic achievement (*Estimate*=53.41, *SE*=23.87, $z=2.24$, $p<.05$). At the item level, words that were more frequent in Spanish were produced more accurately (*Estimate*=69.52, *SE*=24.74, $z=2.81$, $p<.01$).

3.2. Functional neuroimaging

3.2.1. Language activation

The 20 Spanish no-competitor trials were compared to 20 English language trials matched for target and filler picture frequency, neighborhood size, concreteness, familiarity, and imageability (all *ps*>.05) with the Spanish trials. Accuracy was 89.7% (SD=17.36) in the Spanish language no-competitor trials, and 88.3% (SD=4.20) in the English language no-competitor trials. There was no change in model fit after adding Language to the base model, $\Delta LL=1.26$, $X^2(1)=2.53$, *n.s.* Response time was 1766.5 ms (*SD*=290.87) in the Spanish no-competitor trials, and 1721.7 ms (SD=335.18) in the English no-competitor trials. There was no change in model fit after adding an effect of Language, $\Delta LL=0.26$, $X^2(1)=0.51$, *n.s.* The behavioral results indicate that participants learned the Spanish words sufficiently well to perform the picture identification task to comparable levels in both languages.

Differences in cortical activation in response to English and Spanish auditory targets in the absence of a competitor were assessed with paired *t*-tests contrasting the 20 Spanish no-competitor trials with the 20 matched English no-competitor trials (Table 3A). English targets elicited greater activation in bilateral precuneus extending into anterior cuneus, and in the left angular gyrus/inferior parietal lobule (Fig. 1A). Spanish targets elicited greater activation in the left hippocampus (Fig. 1B).

3.2.2. Cross-linguistic competition

The 20 Spanish competitor trials were compared to the 20 Spanish no-competitor trials to assess the effect of cross-linguistic competition on novel language processing. Overall response time was 1804.2 ms (SD=320.2) during the task, with 1841.9 ms (*SD*=351.4) RT for Spanish competitor trials, compared to 1766.5 ms (*SD*=290.87) for Spanish no-competitor trials, a difference of 75 ms. Adding Condition to the base model (Table 2B) had

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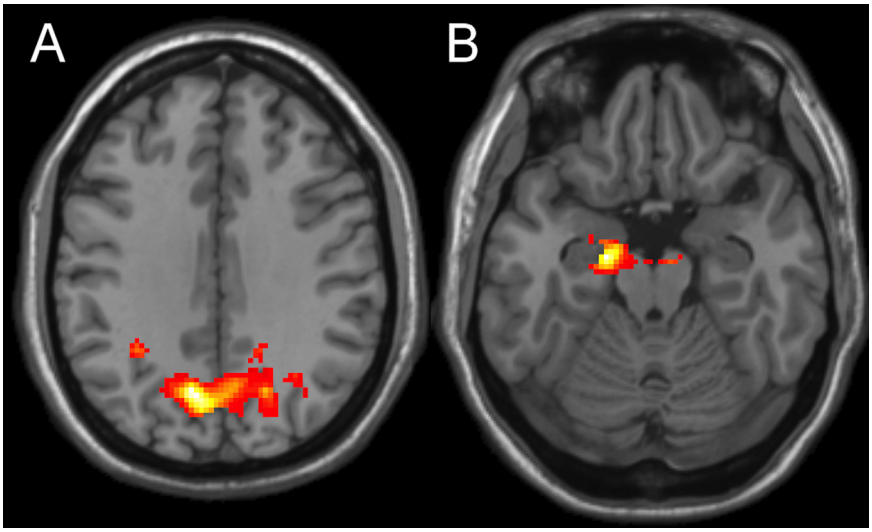

Fig. 1. Language-specific activation during spoken word processing. (A) Spoken English words activated a posterior parietal-temporal network including bilateral precuneus/cuneus and the left inferior parietal lobule (axial slice at z=34, MNI template). (B) Newly-learned spoken Spanish words increased activation of left hippocampus compared to English words (axial slice at z=−20, MNI template).

Table 2
Parameter estimates for mixed effect model of response time on the phonological competition fMRI task.

Parameter	Estimate	SE	*z* Score
Intercept	3.239	0.015	212.70***
Condition	0.015	0.007	2.27*

SE=Standard error. Condition factor zero-centered with Unrelated trials as the reference level.
* $p < .05$.
*** $p < .001$.

Table 3
Effects of spoken word processing and phonological competition.

			MNI coordinates		
Cortical region	Brodmann's area	Cluster size	x	y	z
(*A*) *Language differences*					
English > Spanish					
Left precuneus/cuneus	7/17	2027	−10	−68	34
Right precuneus/cuneus	7/17	–	18	−68	38
Left angular gyrus/inferior parietal lobule	39	–	−33	−39	34
Spanish/English					
Left hippocampus	–	493	−20	−12	−20
(*B*) *Spanish cross-linguistic competition*					
Competitor > unrelated					
No suprathreshold clusters	–	–	–	–	–
Unrelated > competitor					
Left hippocampus/amygdala	–	998	−32	−6	−14

Voxels thresholded at $p < .01$ with a minimum cluster size of k=442 contiguous voxels to yield a cluster threshold of $p < .05$. Coordinates indicate maximum intensity voxel peaks within a cluster.

a significant effect on model fit, ΔLL=2.57, X^2 (1)=5.14, $p < .05$, with a parameter estimate of .015 (*SE*=0.007, *z*=2.27, $p < .05$). Overall accuracy during the phonological competition task was 88.8% (SD=17.78), with 87.8% (*SD*=18.65) of Spanish competitor trials correct, and 89.7% (*SD*=17.36) of Spanish no-competitor trials. There was no change in model fit after adding an effect of Condition, ΔLL=0.59, X^2 (1)=1.18, *n.s.* Results indicate that the presence of an English phonological competitor affected processing of newly-learned Spanish words by increasing response time but did not influence task accuracy.

The neural effect of English cross-linguistic phonological competitors on Spanish word recognition (e.g., *sobre–soap*) was assessed by contrasting Spanish competitor trials with Spanish no-competitor trials (Table 3B). A difference in neurological activation was observed in a cluster extending from the left hippocampus to the left amygdala, with less activation for competitor trials relative to no-competitor trials (Fig. 2).

4. Discussion

The current study investigated the initial stages of second language learning and processing in English monolinguals who were taught Spanish vocabulary. Our first aim was to compare auditory processing of native language words and newly-learned words in a second language. We observed distinct patterns of neural processing of Spanish and English words during spoken word comprehension, with increased hippocampal activation for Spanish language trials and greater activation in posterior parietal regions for English. Our second aim was to determine the extent of native-language interference during second language processing. We saw that in the Spanish language trials, cross-linguistic interference from English led to differences in activation in the hippocampus, which manifested behaviorally as delayed response times in the presence of a cross-linguistic phonological competitor. Participants' ability to learn Spanish words was affected by a combination of cognitive and linguistic factors, including phonological memory, inhibitory control, and academic achievement, as well as English phonetic similarity and Spanish word frequency.

After Spanish word training, we observed differences in whole-brain activation during English and Spanish language trials. Even though accuracy and RT were equivalent between tasks in the two languages, there were differences in neural processing. English trials led to increased activation of several multimodal integration areas, including the left inferior parietal lobule (IPL), left angular

Please cite this article as: Bartolotti, J., et al., Neural signatures of second language learning and control. Neuropsychologia (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.04.007

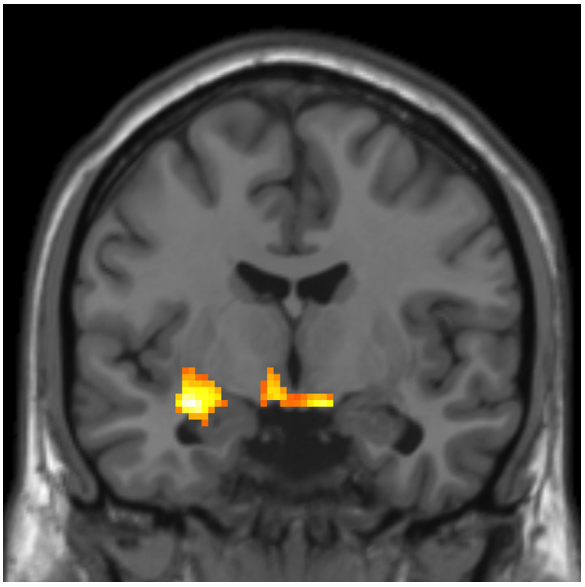

Fig. 2. Cross-linguistic phonological competition. During Spanish word processing, the presence of an English phonological competitor (e.g., target *sobre* [envelope] and competitor *soap*) decreased activation in left hippocampus/amygdala (coronal slice at y = −6, MNI template).

gyrus, and cuneus/lingual gyrus. The IPL plays a role in semantic integration and phonological processing and is associated with increased language experience (Baddeley, 2003; Li et al., 2014; Mechelli et al., 2004). The left lingual gyrus is primarily involved in visual processing and visual-spatial memory (Burianova et al., 2010; Ragland et al., 2002), but also plays a role in language processing tasks that involve visually presented objects, including picture naming (Hocking et al., 2010) or identification (Mueller et al., 2014). Compared to the Spanish trials, the English language trials involved retrieval of known vocabulary for picture names in response to the auditory prompt, which is consistent with the observed recruitment of posterior parietal regions.

In contrast, the Spanish language trials led to increased activation primarily in the left hippocampus compared to English trials. The hippocampus has been shown to be consistently involved in second language vocabulary learning, particularly in paired associate learning (Breitenstein et al., 2005; Flöel et al., 2008), similar to participants' learning task in the current study. Notably, hippocampal recruitment occurs more during early stages of learning, and its activation decreases following vocabulary consolidation and distribution to neocortex (Davis and Gaskell, 2009; Henke et al., 1999). Our results provide additional evidence for the involvement of the left hippocampus in second language vocabulary learning, by demonstrating that immediately post-training, there is differential activation of the hippocampus during processing of a second language compared to the native language. The presence of these cortical differences despite comparable behavioral performance in the two tasks highlights the utility of more sensitive measures when studying language processing.

Because linguistic input activates multiple languages non-selectively (Colomé and Miozzo, 2010; Green, 1998; Marian and Spivey, 2003a, 2003b; van Hell and Dijkstra, 2002), second language learners are confronted with a potentially difficult task. Words in the second language will result in activation of native-language knowledge, which can strongly compete due to large differences in proficiency. Second language learners partially manage this interference by strongly inhibiting the first language during second language processing, as seen in asymmetric switch costs between languages (Costa et al., 2006; Meuter and Allport, 1999). Contributing to the second language learner's difficulty is the novelty of cross-linguistic competition. Although monolinguals encounter phonological competition within their native language in response to auditory words (Allopenna et al., 1998; Eberhard et al., 1995), competition between languages includes an additional component of non-target language activation.

In prior research on second and third language learning using eye-movement and computer mouse-movement trajectories, we observed that bilinguals can control interference by increasing attention to target item activation, whereas monolinguals experience direct competition from the native language that directs attention away from the target (Bartolotti and Marian, 2012). This difference in monolinguals' and bilinguals' ability to manage cross-linguistic competition suggests that there are unique components to between- versus within-language interference that emerge at early stages of second language learning. In the current study we were able to assess the cortical components related to monolinguals' ability to control between-language competition. Though overall accuracy was not affected by the presence of a phonological competitor, we observed a delay in response times and a decrease in hippocampus activation associated with cross-linguistic competitors during processing of words in a newly-learned language. This effect of cross-linguistic interference is distinct from patterns of within-language competition (Marian et al., 2014; Righi et al., 2009). Native language interference at early stages of second language learning may affect memory retrieval, before learned words can be stored in neocortex. Because lexical representations are less stable at these early stages, it is possible that long-term retention of novel words may be disrupted when the native language becomes activated due to cohort competition. The changes required for a monolingual to accommodate a second language can in turn alter native language processing (Chang, 2012; van Hell and Dijkstra, 2002; Zou et al., 2012). The mechanisms of this adaptation constitute a promising area of future study.

Monolinguals' ability to recognize novel words after training was associated with high phonological memory and lower sequence memory. There is a clear relationship between short term memory and vocabulary learning in both children and adults (Atkins and Baddeley, 1998; Baddeley et al., 1998; Gupta, 2003; Service, 1992), and some indication that phonological memory (nonword repetition) and serial recall make different contributions to word learning ability. For word production in adults, serial recall (but not nonword repetition) predicts accuracy for newly learned words (Gupta, 2003). In this manner, serial recall facilitates correct word production via accurate temporal sequencing. However, when the entire sequence is provided to the learner, as in our recognition task, this type of serial recall may not determine task performance. Instead, the critical component required for word recognition is the strength of the initial learned association between a novel word and its conceptual meaning. This association depends on accurate representation of novel word forms, a skill better captured by nonword repetition performance. Although nonword repetition and serial recall ability are often related, the contrasting patterns found for the two abilities on the current task suggests that participants may have utilized different word learning strategies depending on their phonological memory vs. serial recall skill.

Novel word production accuracy, in contrast, was affected by a combination of cognitive and linguistic factors. Better inhibitory control (indexed by smaller Simon effect scores) was associated with higher production accuracy, as was participants' academic achievement (grade point average). Vocabulary production in a second language requires selective attention to the correct form in the second language, while inhibiting the corresponding native language word. Bilinguals, who continually control access to two languages, have better executive functioning than monolinguals as a result of their unique language experience (e.g., Bialystok, 2015;

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Table A1
Stimuli displays for the Spanish phonological competition task. Each target appeared in two trials, once paired with the competitor and unrelated objects, and once paired with the control and unrelated objects.

Target	Competitor	Control	Unrelated 1	Unrelated 2
Bisagra (hinge)	Bees	Notebook	Kite	Funnel
Castor (beaver)	Cast	Moon	Pot	Wheel
Choza (hut)	Choke	Tail	Stapler	Brick
Clima (weather)	Cleaner	Choke	Donkey	Spider
Conejo (rabbit)	Comb	Garlic	Waiter	Tire
Foca (seal)	Folder	Leaf	Vest	Mop
Garra (claw)	Garlic	Plunger	Ring	Stool
Gota (raindrop)	Goat	Tweezers	Wallet	Maze
Hilo (thread)	Eel	Folder	Cymbals	Mouse
Iglesia (church)	Eagle	Cleaner	Paper	Strawberry
Libro (book)	Leaf	Comb	Skunk	Typewriter
Licuadora (blender)	Leak	Tent	Squirrel	Referee
Mitad (half)	Meat	Leak	Bull	Ashtray
Muñeca (doll)	Moon	Cast	Sword	Jar
Novia (bride)	Notebook	Eel	Traffic light	Puppet
Plancha (iron)	Plunger	Bees	Walnut	Stroller
Sobre (envelope)	Soap	Meat	Paintbrush	Fin
Telaraña (web)	Tail	Soap	Ostrich	Present
Tenedor (fork)	Tent	Eagle	Net	Bread
Tuerca (nut)	Tweezers	Goat	Helmet	Skirt

Blumenfeld and Marian, 2013). Inhibitory control skill is thought to contribute to differences between monolinguals and bilinguals in terms of second/third language learning ability (Bartolotti and Marian, 2012; Kaushanskaya and Marian, 2009a, 2009b), and here we observe that within monolingual speakers of English, differences in inhibitory control ability do affect word learning performance.

At the individual word level, we observed that the frequency of Spanish words was associated with the likelihood that participants were able to correctly produce the target word. Although all participants reported no Spanish language training, they may have been exposed to some Spanish during their lives. Because we selected Spanish words for training across a range of frequencies, it is possible that participants had prior exposure to high frequency items prior to training, providing a learning and memory advantage.

In conclusion, we find evidence for cortical differences in how first and second languages are processed during the earliest stages of vocabulary acquisition in a second language. Whereas native language processing relies to a greater degree on posterior parietal regions, novel second language vocabulary recruits the hippocampus, consistent with the hippocampus's role early on in memory formation. Further, monolinguals begin to experience cross-linguistic competition from the native language at the onset of second language learning in the same cortical areas used for novel word retrieval. Proficient users of a second language typically show notable differences in first and second language processing and use; our work demonstrates that these differences may be rooted in changes that occur at the onset of learning.

Acknowledgments

This research was supported in part by Grants NICHD R01 HD059858 to VM, T32 NS 47987-8 to JB, and NIH/NICHD R03HD079873 to AH. The authors would like to thank the members of the Northwestern University Bilingualism and Psycholinguistics Research Group for comments on this work.

Appendix

See Tables A1 and A2.

Table A2
Whole-brain activation by language.

Cortical region	Brodmann's area	Cluster cize	MNI coordinates x	y	z
English language trials					
Left supplementary motor area/superior frontal gyrus	6	195	2	2	54
Right insula	13	48	34	16	2
Right superior temporal pole/insula	38/13	83	52	6	0
Left insula	13	12	−42	−4	12
Right lingual gyrus	19	54	16	−64	−12
Left precuneus	7	37	−30	−48	50
Right fusiform gyrus	37	33	38	−58	−20
Right inferior occipital gyrus	19	20	42	−74	−10
Left cerebellum	–	15	−26	−62	−18
Spanish language trials					
Central supplementary motor area/cingulate gyrus	6/32	319	0	2	52
Left inferior parietal lobule	40	238	−38	−44	44
Right insula	13	153	44	−2	2
Right cerebellum	–	157	36	−62	−22
	–	28	14	−74	−16
Left cerebellum	–	108	−20	−60	−16
Left lingual gyrus	19	77	−12	−54	0
Left inferior frontal gyrus	9	62	−36	8	30
Right middle occipital gyrus	19	47	34	−72	28
Right precuneus/superior occipital gyrus	7/19	30	20	−70	32
Right supramarginal gyrus	40	26	50	−18	24
Left supramarginal gyrus	40	25	−52	−26	22
Central lingual gyrus	17	25	2	−88	0
Right inferior occipital gyrus	19	19	42	−74	−12
Right angular gyrus	39	19	30	−56	42
Left middle occipital gyrus	37	15	−46	−70	−10

Voxels thresholded at $p < .05$, FWE corrected with a minimum cluster size of k = 10 contiguous voxels; English $t = 7.21$, Spanish $t = 7.26$. Coordinates indicate maximum intensity voxel peak within a cluster.

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Please cite this article as: Bartolotti, J., et al., Neural signatures of second language learning and control. Neuropsychologia (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.04.007

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Please cite this article as: Bartolotti, J., et al., Neural signatures of second language learning and control. Neuropsychologia (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.04.007