Neural signatures of inhibitory control in bilingual spoken production

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Abstract

Bilinguals activate both languages when they intend to speak even one language alone (e.g., Kroll et al., 2006). At the same time, they are able to select the language they intend to speak and switch back and forth between languages rapidly, with few production errors. Previous research utilizing behavioral (Linck et al., 2009) and neuroimaging techniques (ERPs and fMRI; Guo et al., 2011; Misra et al., 2012) suggest that successful bilingual speech production is enabled by active inhibition of the language not in use. Results showing an asymmetric switching cost for the L1 compared to the L2 (with a larger cost -reflected in longer naming latencies- when switching from the L2 to the L1) have been taken as evidence that the L1 (usually the dominant language for bilinguals who learned their second language later in life) may need to be inhibited when speaking in the L2. However, there is still little research on the scope of this inhibitory process. The goal of this event-related functional magnetic resonance imaging study is to understand how the recruitment of neural areas implicated during bilingual language processing are shaped by the scope of language use. The results show that bilinguals engage a wide functional control network that is hierarchically engaged in local control for single lexical items, but extends further to the broader semantic level, and finally to the whole language. This functional network is modulated by proficiency in the L2.

Keywords

bilingualism; language production; inhibitory control; proficiency

Bilingual language processing: Neural signatures of hierarchical bilingual language control.

In the past twenty years, research on bilingual language processing has shown that it is virtually impossible for bilinguals to avoid the activation of both languages. The activation

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of both languages has been observed when speakers intend to speak one language alone (e.g., Costa, 2005; Kroll et al., 2006, Román et al., 2015; Parker Jones et al., 2012), and even when the environment is strongly biased toward one language or when the interlocutor is monolingual. At the same time, under special circumstances, bilinguals are able to move in and out of the two languages with fewer processing costs than might be expected (e.g., Kootstra et al., 2010; Myers-Scotton, 2006). These observations suggest that bilinguals possess a powerful control mechanism that allows them to monitor language activation.

The Inhibitory Control -IC- model (Green, 1998) proposes that for bilinguals to speak the less dominant of their two languages, they may need to temporarily inhibit the more dominant of the two languages (e.g., Green, 1998; Levy et al., 2007; Linck et al., 2009; Philipp et al., 2007). If both languages are activated even when bilinguals intend to speak one language alone, inhibiting the stronger language will have the desired effect of allowing the weaker language to be spoken. The IC model has been supported by an increasing number of studies showing that negotiating between two languages engages a number of brain regions that are implicated in domain general cognitive control, encompassing the prefrontal cortex, anterior cingulate cortex -ACC-, and basal ganglia, including left caudate/putamen (Branzi, Della Rosa, Canini, Costa & Abutalebi, 2016; Abutalebi, Miozzo & Cappa, 2000; Pliatsikas & Luk, 2016; Stocco & Prat, 2014; for ERP evidence see Jackson, Swainson, Cunnington, & Jackson, 2001, and Christoffels et al., 2007). These findings suggest that bilinguals utilize language non-specific, domain-general cognitive processes to control, monitor and inhibit the strongest language to successfully produce the intended language (Abutalebi & Green, 2007; Abutalebi et al., 2011).

In addition, functional activation in naming has been found to differ between bilinguals and monolinguals, even when bilinguals are in a single L1 language environment (Parker Jones et al., 2012), suggesting that bilingualism might reshape the engagement of control networks more broadly, even when speaking the L1 alone. For example, Parker Jones et al. (2012) tested participants during a naming paradigm in both languages on separate days. Results revealed that bilinguals showed greater activation in the left pars opercularis and pars triangularis (POp and PTr), areas that were instead activated by monolinguals during a verbal Stroop task (Parker Jones et al., 2012). The authors concluded that Pop and PTr are areas that are implicated in bilingual language control even when in a single language context. In that study, the authors did not observe the activation of other control areas that have been implicated in bilingual language control, such as ACC or left caudate, however, their study did not involve any language switching, and bilinguals' two languages were tested in separate days.

A number of past studies have examined bilingual language control using switching paradigms, using tasks where the languages change from trial to trial, and blocked naming tasks in which bilinguals are required to switch languages across blocks. For example, Misra et al. (2012) tested the IC hypothesis using an event-related potential (ERP) version of the blocked naming paradigm in which Chinese (L1)-English (L2) bilinguals named pictures in each of their languages, one after the other. Ordinarily, repetition of identical pictures would be expected to produce response facilitation in the subsequent blocks, regardless of which language is spoken. If inhibition of the native language (L1) occurs when bilinguals produce

speech in the second language (L2), then there should be a cost for switching from the L2 into the L1 and repetition priming effects would be eliminated. Misra et al.'s results confirmed this prediction. When pictures were named first in the L2 and then were repeated in the L1, a sustained modulation of the N200 (an ERP index of response conflict, e.g., Jackson et al., 2001) was observed even following many trials. Importantly, a modulation of the N200 was not observed when participants switched from the L1 to the L2. Using a similar design, Guo et al. (2011) used functional magnetic resonance imaging (fMRI) to determine what neural networks were at play during bilingual language switching and language mixing in highly proficient Chinese-English bilinguals. In that study, a group of bilinguals named a block of pictures in Chinese (the L1), and then a block of pictures in English, the L2. Another group of bilinguals first named a block of pictures in English, and then a block of pictures in Chinese. Results showed that the dorsolateral prefrontal cortex and parietal cortex were more activated when the L1 followed the L2 in blocked naming.

Critically, neither the Misra et al. nor the Guo et al. studies were designed to address the scope of inhibitory control. The items used in those studies were identical and repeated from block to block. In this way, the effect of inhibition during bilingual language production was only assessed for those items that were previously named (and inhibited) either in the L1 or L2. As such, those results can not address the issue of whether the scope of the observed inhibition extends beyond the specific items that were named previously, or whether inhibition extends beyond the single word level to the semantic category, or even more broadly to the entire language. Two recent studies addressed the issue of the scope of inhibition during bilingual language production. Van Assche, Duyck and Gollan (2013) used a language-blocked behavioral phonological verbal fluency task to ask if Dutch-English and Chinese-English bilinguals would show a similar global inhibitory effect on the L1 when accessing words through phonological retrieval. The task was administered such that a subset of participants performed the letter fluency task in their L1 first and then in the L2, while another subset of participants performed the task in the opposite order. More specifically, to examine the scope of inhibition, participants performed the task for three letter categories (F/A/S) in both languages, i.e., "same letter category", while in the "different letter category condition" participants performed the task using some letters in one language (i.e., B/I/L) and different letter categories (M/O/N) in the other language. Critically, Van Assche et al. predicted that if bilinguals temporarily inhibit the whole language to allow for L2 production, reduced verbal fluency should be observed not only for the same category letter condition (which would signal "local" language inhibition) but also for the different category condition. The results replicated the block order effect reported by Misra et al. (2012) – letter fluency was reduced for the dominant language when it followed the less dominant language. Both bilingual groups showed the effect when they had to produce the same letter category. However, only bilinguals with lower L2 proficiency showed reduced letter fluency for the different letter condition, signaling global inhibition of the native language during L2 processing. These results suggest that all bilinguals show evidence of inhibitory processing, but that relative proficiency in the L2 may determine the scope of the observed inhibition.

In an event-related fMRI study, Branzi et al. (2016) asked whether the control network during bilingual language processing changes under conditions of local or global control.

Local control denoted to the repetition of a restricted set of lexical items while global control referred to the entire language system. In that study, participants performed a blocked picture naming task that included pictures from a variety of semantic categories. To capture differences between local and global control, a subset of pictures was repeated between the L1 and the L2 block, while another subset was composed of novel pictures that had not been seen before. The authors reported that different brain regions were engaged when bilinguals exerted local or global control. They identified the dorsal portion of the anterior cingulate cortex (dACC) and the presupplementary motor area (pre-SMA), as being active during local control, while prefrontal inferior parietal areas and the caudate appeared to be important for both global and local control. Like Van Assche et al. (2013), Branzi et al. also reported an effect of proficiency, such that the left caudate was more activated during L1 naming, and dACC/pre-SMA appeared to be activated exclusively during L2 naming.

The main goal of the present study is to examine the neural underpinnings of bilingual language production and language control using fMRI to determine if and to what extent the affected neural areas are modulated by the scope of inhibition. More specifically, we ask how broadly the L1 is inhibited after naming in the L2 with respect to scope, i.e., across specific words previously named, or more globally spreading to the semantic level, or the entire language. Similar to the Misra et al. (2012), Guo et al. (2011), and Branzi et al., (2016) paradigms, English (L1)-Spanish (L2) bilinguals and a control group of English monolinguals named pictures in a blocked-naming paradigm, alternating languages across blocks. However, in contrast to previous studies, the pictures were not identical but drawn from different semantic categories across languages. As will be explained in more detail in the Methods section, items named after the second run were 1) repetitions of the items named previously in English or Spanish, 2) novel items drawn from the same semantic categories that were presented previously, or 3) completely new items from categories not previously named in either language. This allowed us to ask whether the pattern of neural activation differs as a function of prior exposure (at the item, category, or language level).

According to the IC hypothesis (Green, 1998), and other recent models of bilingual language control (Abutalebi & Green, 2007; Abutalebi et al., 2011; Green & Abutalebi, 2013), if bilinguals inhibit their native language during L2 production, we should observe activation in brain areas dedicated to cognitive control when naming in the L1 following naming in the L2. These areas encompass both cortical and subcortical regions, including the anterior cingulate cortex -ACC-, basal ganglia (caudate and putamen), and dorsal frontal-parietal network (Luck et al., 2011; Abutalebi & Green, 2007). If inhibition is highly focused, only the repetition of the same pictures should elicit behavioral inhibition, and show increased activation in these regions (i.e., ACC, pre-SMA, and caudate, and putamen, e.g., Branzi et al., 2016). Under the same hypothesis, items not previously named but drawn from semantic categories that were previously presented or completely new items should not produce a neural pattern consistent with inhibition. However, we hypothesize that if language control generalizes within a semantic domain, naming new items from previously seen semantic categories might also be expected to show evidence of activity in neural areas that are dedicated to language control. If inhibition is a global phenomenon that temporarily applies to the entire language, then we would expect behavioral inhibition and increased activation within the control network to be engaged even when naming completely novel items from

categories that have not been previously named. Critically, the pattern of activation observed in bilinguals should not be seen in monolinguals.

Finally, because previous research has revealed that the recruitment of neural substrates during bilingual language control is often modulated by proficiency in the L2 (e.g., Bartolotti et al., 2016; Branzi et al., 2016; Guo et al., 2011; Parker Jones et al., 2012), and given the growing body of literature demonstrating that speaking a second language or being immersed in a second language environment influences the behavioral, functional and structural substrates of the native language (Linck, Kroll & Sunderman, 2009; Parker Jones et al., 2012; Rossi et al., 2017), a key issue is whether proficiency in the L2 modulates recruitment of control regions. If higher levels of L2 proficiency require more control, a positive correlation between L2 proficiency and functional activation in the control network should be observed.

METHODS

Participants

A total of 56 participants were recruited for this study. All were students at the Pennsylvania State University and had comparable education level. Participants provided informed consent and were paid for their participation. Experimental procedures for data collection and analysis were approved by Institutional Review Boards of the Pennsylvania State University, Indiana University, and Duke University. All were right-handed healthy young adults with normal or corrected to normal vision. None reported a history of neurological or psychological disorders, or any major medical conditions (e.g., diabetes, heart disease), and none were taking any medication that might affect the brain or blood flow. Thirty were native English speakers who spoke Spanish as their L2, and 26 were monolingual English speakers who were recruited to participate as the control group.

Out of the thirty L2 Spanish participants, 5 had to be excluded: one for technical problems during scanning and four because of low proficiency in the L2 naming block (< 35% correct naming). Twenty-five bilingual participants were therefore included in the final analysis (mean age 23.9; age range 20–35; 16 females). For the English controls, 4 participants were excluded for excessive motion, yielding a final sample of 22 participants (mean age 21.5; age range 18 – 27; 12 females).

All participants completed a language history questionnaire (LHQ) in which they self-rated their language abilities in each language on a scale from 1–10 (1 = no proficiency; 10 = native-like proficiency). English monolinguals reported minimal or no knowledge of a second language and they rated their English proficiency at the highest levels ($\mu = 10$. SD = 0.2). Bilinguals also rated their English proficiency very highly ($\mu = 9.9$; SD = 0.3), and their average L2 proficiency was intermediate/high ($\mu = 7.5$; SD = 1.1). The full language history questionnaire is reported in Appendix A.

In addition to completing the LHQ, bilinguals completed an independent assessment of their language ability in Spanish by completing the Diploma de Español como Lengua Extranjera, -DELE- Spanish grammar task (DELE, http://www.dele.org/, Ministry of Education Culture

and Sport of Spain, 2006). A composite score of L2 language proficiency was calculated based on the DELE score, L2 self-ratings, and naming accuracy in the L2 (Spanish) in the main experimental task. The composite score for each participant was calculated as follows: raw scores were standardized to z-scores and were summed together within each participant; then the resulting score was divided by the square root of the sum of the variances and covariances of all the subtests (Crocker & Algina, 1986; McMurray, Samelson, Lee, & Tomblin, 2010; Pivneva, Palmer, & Titone, 2012). Language measures for the bilingual group are reported in Table 1.

Materials, experimental design and procedure

Materials—The experimental task was speeded picture naming. During the task, participants named a total of 576 pictures. The pictures consisted of images taken from 9 semantic categories: animals, body parts, fruits and vegetables, clothing, kitchen items, furniture, tools, musical instruments, and vehicles. They were presented as line drawings, black and white photographs, or color photographs to allow for concept repetition, but to minimize perceptual priming. Line drawings were selected from a standardized picture database (Snodgrass & Vanderwart, 1980). For each line drawing, color counterpart photographs were found through freely available websites. The black and white pictures were derived from the colored pictures and were therefore identical other than the absence of color. All images were 300×300 pixels and in bitmap image format. Across categories pictures were matched for frequency and imageability. All stimuli were presented using the Brain Logics MRI Digital Projection System, and experimental parameters were controlled via E-prime. Responses for accuracy analysis were recorded with an MR compatible microphone (Resonance Technologies, Northridge, CA). Examples of the pictures and experimental design are provided in Figure 1.

All pictures (colored pictures, black and white pictures, and line drawings) were normed in two separate studies with participants who matched the demographics of the monolinguals tested in the main fMRI study. In Study 1, 25 young adult monolingual English speakers were tested in a self-paced picture naming study. Each item was presented one at a time, in a randomized order, while we collected naming accuracy and RT data. In Study 2, 24 young adult monolingual English speakers were tested in a picture naming study in which we specifically mimicked the picture presentation rate that was used during the main fMRI study (i.e., two pictures were presented one after the other (duration = 800ms, ISI = 200ms), followed by a variable inter-trial-interval (ITI range = 6.2 to 14.2s, average ITI = 9.2s). Results confirmed that the accuracy rate for all the pictures was very high in both norming studies (Study 1 accuracy = 87.6%; Study 2 accuracy = 88.2%), and there was no significant difference between studies (Pearson's Chi square = 1.73; p = 0.095). A further analysis comparing accuracy by presentation mode (i.e., Colored pictures, Black and white pictures, and Line drawings) showed that the overall accuracy across the three presentation modes was very high in both experiments (colored pictures = 88.9%; black and white pictures = 89.5%; line drawings = 86.3%). A chi-square analysis revealed that there was a significant difference in naming accuracies across the three presentation modes, with line drawings being named slightly less accurately than colored and black and white pictures. Naming latencies for correct items were analyzed using a 1-way, repeated measures ANOVA

examining presentation mode (colored pictures, black and white pictures, and line drawings). Results showed that across the three presentation modes, the line drawings produced slightly longer RTs than than colored and black and white pictures (F = 14.5; df = 2; p = 0.01)[1]. These results suggest, overall, that all pictures were named relatively quickly and accurately, and that the photographs were comparable to the more well-established Snodgrass and Vanderwart normed drawings. In addition, a naming agreement score was calculated for all items that were named with an accuracy score up to 80% correct. For each item the number of consistent namings, and the number of deviant namings was coded across all participants. For example, for the item *tambourine*, we scored all the times the item was named as tambourine, and the number of times in which the item was named in a different way i.e., "maracas". Target naming plus deviant namings constituted the total number of namings (excluding no productions). A naming agreement score was then calculated by dividing the number of target namings by the number of deviant naming. A correlation analysis revealed that the accuracy score and the naming agreement scores are highly correlated (Pearson's r = 0.88; p < 0.001).

Experimental design—The picture naming task was subdivided into 8, 6-minute runs. In the first two runs, pictures were presented in a categorically blocked order. In each run, participants named 8 items per category. Each individual picture was repeated in each of the three visual formats. Thus, there were a total of 24 items per category. There were 3 categories per run, making a total of 72 items to be named in each of the first two runs. Crucially, the task was specifically designed to induce language switching in bilinguals. In Run 1, bilinguals were instructed to name items in their L1 (English). In Run 2 they named items in the L2 (Spanish), requiring a language switch. Finally, for runs 3–8, they were instructed to switch back to their L1 again, and name only in English. In Runs 1 and 2, two distinct sets of semantic categories were used to enhance the perceived separation between the two runs. During Run 1, participants named items that were drawn from "natural" semantic categories (i.e., Animals, Body Parts, Vegetables), while during Run 2, they named items from three other "artifact" categories (i.e., Clothing, Kitchen Items, Furniture). Following Runs 1 and 2, participants completed six additional naming runs (Runs 3–8) in which they were required to switch back to their L1 (English). During those runs, participants named all the items that were previously named in Runs 1 and 2. Runs 3–8 also contained new items that were not previously named. That comparison is important as it allows us to determine whether effects generalize beyond the specific items named. As noted earlier, these new items included items from the semantic categories that were previously named in the L1 (e.g., new animals), new items from the semantic categories that were previously named in the L2 (e.g., new items of clothing), and completely new items from three novel categories (tools, instruments, and vehicles). This yielded 5 categories of items: item repetitions, previously named in English; item repetitions, previously named in Spanish; new items from a category of items that was previously named in English; new items from a category of items that was previously named in Spanish; and new items from new categories. Across Runs 3–8, participants named all of the pictures previously seen in Runs 1 and 2 (144 items), 72 new items each from the old semantic categories presented in

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[1]A boxplot figure showing the comparison for the norming study is provided in Appendix A (Figure A).

Runs 1 and 2 (144 items total), and 144 completely new items taken from new semantic categories.

Across Runs 3–8, item presentation was presented in a fully randomized order, not blocked by semantic category. The composition of the new conditions represented a mixture of animate and inanimate categories so that the planned comparison between naming old versus new items was not biased towards one of the previously named languages. The addition of the new pictures from previously named semantic categories as well as completely new pictures, was essential to test whether inhibitory control extends beyond the item level. Monolingual participants completed the same protocol with the exception that pictures in Run 2 were named in English. A schematic representation of the experimental paradigm is presented in Figure 2.

To facilitate naming, minimize motion, and enable collection of behavioral responses, we incorporated a sparse sampling fMRI technique. Using this technique, each time point consisted of 2 seconds of data collection and 2 seconds of silence (functional TR = 4s)[2]. To maximize stimulus presentation within this design, we presented two pictures within each period of silence (duration = 800ms, ISI = 200ms). Pairs of pictures were followed by a variable inter-trial-interval (ITI range = 6.2 to 14.2s, average ITI = 9.2s) which has been shown to provide better signal recovery compared to fixed intervals (Optseq2, Dale, 1999). Because the hemodynamic response is relatively slow, pairs of items were modeled as one trial in the fMRI analyses and pairs always included items from the same category. Each run began and ended with the presentation of a fixation cross and a fixation cross was presented between each item.

Procedure—Participants completed a safety screening form and the informed consent. They first performed a practice session in a dedicated mock-scanner facility. During that session, they practiced the task to familiarize themselves with the experimental procedure, specifically to get used to the sparse sampling procedure and naming the items during the two seconds of silence. Pictures used during the practice session did not appear in the actual experiment. Just prior to the experimental task, participants were reminded to overtly name pictures only during the 2 seconds of silence. After the study was completed, participants were debriefed.

MRI Data Acquisition

MRI scanning was conducted with a Siemens 3.0 Tesla Magnetom Trio whole-body, human scanner (60 cm bore, 40 mT/m gradients, 200 T/m/s slew rate). An eight-channel head coil was used for Radio Frequency (RF) reception (Siemens Healthcare, Erlangen, Germany). Sagittal T-1 weighted localizer images were acquired and used to define a volume for high order shimming. The anterior and posterior commissures were identified for slice selection and shimming. A semi-automated high-order shimming program was used to ensure global field homogeneity. High-resolution structural images were acquired using a 3D MP-Rage

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[2]2 The sparse sampling technique involved inserting a 2 second pause following the collection of each whole brain volume. Thus, the first 2 seconds of the 4 second TR involved data acquisition with the typical associated scanner noise, followed by a second period of silence in which the scanner was not collecting data and during which time participants were instructed to name the pictures.

pulse sequence (TR = 1400 ms; TE = 2.01 ms; ti = 900 ms; FOV = 25.6 cm^2; flip angle = 9°; acceleration factor = 2; voxel size = $1 \times 1 \times 1$ mm; 160 contiguous slices). Functional images sensitive to blood oxygen level-dependent (BOLD) contrast were acquired using an EPI pulse sequence (TR = 4 s; TE = 25 ms; FOV = 24cm^2; flip angle = 70°; acceleration factor = 1; voxel size = $3.75 \times 3.75 \times 3.8$ mm; 34 contiguous oblique axial slices, parallel to the AC-PC line, interleaved acquisition). Each of the eight runs consisted of the acquisition of a time series of 100 brain volumes. Two initial RF excitations were performed to achieve steady state equilibrium and were subsequently discarded.

Data Analysis

Behavioral naming data were transcribed for each participant and analyzed for naming accuracy. A two-step procedure was followed. First, omissions, and clearly incorrect namings were scored as "0". An example of a clearly incorrect naming would be producing "tiger" at the presentation of the picture "bear". Then, responses were analyzed for the presence of synonyms, and related items. In line with literature suggesting that producing different names for the same object within an individual might suggest access to partly different lexical representations, we considered the first naming for a given item to be the "correct" one. If the same item was named differently across presentations, we considered it to be incorrect. Overall, the majority of errors were inaccurate responses as defined above or omissions.

The fMRI data were analyzed for quality via a quality assurance tool that quantifies several metrics including Signal-to-Noise ratio (SNR), Signal-Fluctuation-to-Noise ratio (SFNR), motion, and voxel-wise standard deviation measurements (Friedman and Glover, 2006; Glover et al., 2012). Additionally, all data were visually inspected for artifacts and blurring. The average translation in the X, Y, or Z directions was 0.33 mm (range: 0.08 – 1.5 mm), and the average rotation was .006 radians (range: 0 - .08). Thus, none of the included participants exhibited more than ½ voxel equivalent of movement in the X, Y, or Z dimensions, consistent with fMRI best practices. Across groups there were no significant differences in the amount of movement. Moreover, these estimates of motion were included as nuisance covariates in the overall fMRI model. Functional image data were motion-corrected, high-pass filtered, and spatially smoothed using a Gaussian kernel (FWHM= 5 mm). Functional images of each participant were co-registered to structural images in native space, and structural images were normalized to Montreal Neurological Institute (MNI) standard space using FSL's MNI Avg152 T1 $2 \times 2 \times 2$ mm standard brain. The same transformation matrices used for structural-to-standard transformations were then used for functional-to-standard space transformations of co-registered functional images. Co-registration and normalization steps were completed using FSL's FLIRT, which is an affine registration program (Greve & Fischl, 2009; Jenkinson et al., 2002; Jenkinson & Smith, 2001). A double γ function was used to model the hemodynamic response for each trial in each run. We used FSL version 4.1.5 and FEAT version 5.98 for analyses of functional activations (Smith et al., 2004; Woolrich et al., 2009).

Statistical analyses incorporated a mixed effects approach. The first level analyses from each experimental run for each participant were combined and a second level analysis was

performed for each participant. These second level analyses were then combined across participants into a group level analysis to identify voxels that were activated by each condition. Only trials where both items were correctly named were included in these analyses. For runs 1 and 2, the hemodynamic response to items was compared to the implicit baseline (i.e., the fixation cross presented between items). For runs 3–8 explicit comparisons between categories of items were made as described in the results section. All activations were significant at $p < .01$ voxel-level (uncorrected), and $p < .05$ cluster corrected according to Gaussian random fields (GRF) theory in which each cluster's estimated significance level was compared with the cluster probability threshold, and then only clusters whose estimated significance exceeded the threshold were included in the results (Worsley, et al., 2001, Hayasaka & Nichols, 2003). In addition to this, we only considered clusters whose spatial extent exceeded 15 voxels. Because all analyses, including correlational analyses, involved a whole-brain approach, any bias or circularity in the statistical analyses should be minimized (Kriegeskorte et al., 2009). Coordinates of the centers of activation and their corresponding anatomical gyri were determined through the use of anatomical atlases. All reported coordinates are in MNI space and results are overlaid on the MNI template brain.

RESULTS

In this section, we report behavioral and fMRI results that address two main questions. We first consider patterns of activation for bilinguals and monolinguals in Runs 1 and 2. In Run 1, bilinguals and monolinguals are naming pictures in English, the native and dominant language for both groups. A comparison across the Run 1 data will tell us whether actively using an L2 also affects the native language even before the L2 is used explicitly. We can then compare the data for Runs 1 and 2 to examine picture naming then the L2 named. The second question, and the primary analytic goal of this study, was to examine possible differences in activation for bilinguals vs. monolinguals naming pictures in English only in Runs 3–8. The bilinguals will have briefly named pictures in Spanish in Run 2. If the control of the L1 that is required to enable production in the L2 applies only to the concepts actually named, then the consequences of L2 naming should be evident only for identical items that are repeated in Runs 3–8. If the scope of control is broader, then we might see the consequences of bilingual use of L2 not only for identical repetitions, but also for new items from semantically related categories. Finally, if the scope of control is truly global and applied to the entire language, then all naming in L1 should be affected.

Results for Run 1 and 2: Blocked naming in English and Spanish

Behavioral results: In Run 1 monolingual and bilingual participants completed a categorically blocked naming task in English with items from three categories (animals, body parts, and fruits/vegetables). A binomial logistic regression model was fitted to compare monolingual and bilingual naming performance collapsed across. Results show that overall participants had very high accuracy (97%). However, the bilingual group had a higher percentage of correctly named pictures than monolinguals (bilinguals = 98.6% correct; monolinguals = 95.8% correct; p < 0.01). In Run 2, monolinguals performed the naming task in English and bilinguals performed it in Spanish (both groups named clothing, furniture, and kitchen items). As such, a direct comparison of behavioral performance

between the two groups of participants was not particularly informative because although the bilinguals were relatively proficient in L2, they were dominant in L1. The descriptive statistics for the two groups revealed that monolingual English speakers' accuracy in English 99.7% (SD = 0.05) was higher than bilinguals' accuracy in Spanish 85.8% (SD = 0.3). Figure 3 presents the data for Run 1 and Run 2.

Functional fMRI results:

Run 1: Table 2 reports the functional activation results for Run 1 for both groups. Collapsing across all semantic categories within Run 1, for monolinguals there were clusters of activation in bilateral lateral occipital cortex, which extended into the fusiform gyri; bilateral putamen; left thalamus, and left middle frontal gyrus. Bilinguals elicited activation that included bilateral occipital cortex, and extended into neighboring regions including bilateral fusiform and inferior temporal cortex, and bilateral posterior cingulate. Additional activation was also seen in clusters in bilateral inferior parietal cortex that also extended into posterior superior temporal gyri and posterior insular cortex; bilateral precentral gyri; bilateral putamen; bilateral cingulate; and right middle frontal gyrus.

Activation differences in Run 1: A number of recent studies have highlighted how bilinguals' L1 might change as a function of speaking an L2, even when they are in a single language L1 context (Parker Jones et al., 2012; Williams, Darcy & Newman, 2016). If the L1 changes as a function of interaction with a second language, then even when speakers are native and dominant speakers of the same L1, we might expect to see differences in patterns of activation, even before the bilinguals switched into the L2. Table 3 and Figure 4 report the results comparing patterns of activation between monolinguals and bilinguals in Run 1 only. Results show that bilinguals elicited greater activation than monolinguals in right inferior and middle frontal gyrus, left superior frontal gyrus, bilateral supplementary motor cortex, bilateral pre- and post-central gyrus, bilateral anterior cingulate, right posterior insula, left posterior superior temporal gyrus, left supramarginal and angular gyri, left precuneus and posterior cingulate, and left occipital cortex. There were no regions in which monolinguals elicited greater activation than bilinguals.

Run 2: In Run 2, monolinguals named pictures in English and bilinguals named the same pictures in Spanish (clothing, furniture, and kitchen items). For monolinguals, results revealed small clusters of significant activation in bilateral middle and superior frontal gyri, and right occipital fusiform gyrus. For bilinguals, there were large extents of activation in bilateral occipital cortex, which extended into bilateral fusiform gyri and precuneus; bilateral putamen; bilateral middle temporal gyri which extended superiorly in the right hemisphere including superior temporal gyrus, and extended inferiorly in the left hemisphere to include inferior temporal gyrus and temporal pole.

Within group comparisons revealed that there were no significant differences between Runs 1 and 2 for monolinguals. However, for bilinguals a direct comparison of naming in English (L1 in Run 1) and Spanish (L2 in Run 2) revealed that L2 naming elicited significantly greater activation in the left lateral occipital cortex, right fusiform and right posterior inferior temporal gyrus, left caudate, right postcentral and supramarginal gyri, and left middle frontal

gyrus. There were no regions in which naming in English elicited greater activation than naming in Spanish. There was also a significant interaction of Run × Group in right putamen in which monolinguals showed more activation during Run 1 compared to Run 2, and bilinguals elicited more activation in Run 2 (L2 naming) compared to Run 1 (L1 naming) as shown in Figure 5.

Local control: comparing the repetition of items in Runs 3–8 that were previously named in Run 1 in English for monolinguals and bilinguals.—This analysis was important to be able to identify the neural substrates of local bilingual control. Here we examined the pattern of activation for specific items that were named in English in Run 1 and were then, for the bilinguals, were repeated in Runs 3–8 after naming in the L2. The analysis was therefore restricted to performance on lexical items named in Runs 3–8 that were previously named in in English in Run 1. For the monolinguals, the repetition was identical except that Run 2 occurred in English.

Behavioral results: There was a significant effect of Group with bilinguals having higher naming accuracy than monolinguals (bilinguals: 99.5%; monolinguals: 97%, p < 0.01).

Functional fMRI results: During Runs 3–8, when naming items that had been previously named in English, bilinguals elicited greater activation than monolinguals in right pre- and post-central gyri, including the cingulate gyrus (Table 4 and Figure 6 below). Looking at the opposite comparison (i.e., Monolinguals > Bilinguals for items named in Run 3–8 that had been previously named in English), monolinguals elicited greater activation than bilinguals in frontal pole and in the left precentral gyrus (Figure 7)[3].

Beyond local control: pattern of functional activation comparing new items from previously named semantic categories and completely new items

Runs 3–8: Naming items that were previously named in English or in Spanish (for bilinguals)—In these analyses, we investigate if and to what extent bilinguals engage neural areas that are dedicated to language control beyond the specific words that were named previously in the L2 (i.e., local control), at the broader semantic level, and even more globally, to the whole language.

Behavioral results: Results from a binomial logistic regression model were fit on naming performance collapsed across Runs 3–8, with Group (Bilinguals/Monolinguals) and item category (completely new items/new items from old semantic categories named in Run 1) as predictors. This analysis showed a significant main effect of group (p < 0.05) with bilinguals having higher accuracy than monolinguals, and a main effect of item category (p < 0.001) revealing that new items from categories previously named in Run 1 in English were named more accurately than novel items from completely new semantic categories. There was no significant interaction between group and item category.

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[3]An additional table reporting significant functional activation for Runs 3–8 contrasting items identical to the ones that had previously been named in English in Run 1 for the two groups separately is provided in Appendix A (table A).

In an additional analysis, a binomial logistic regression model was fit on naming performance collapsed across Runs 3–8 with Group (Bilinguals/Monolinguals) and item category (completely new items/new items from previously named semantic categories named in run 2 -named in Spanish for bilinguals and English for monolinguals-) as predictors. Results showed a significant main effect of group ($p < 0.05$) with bilinguals having higher accuracy than monolinguals, and a main effect of item category ($p < 0.05$) demonstrating that new items from previously named categories in Run 2 were named more accurately than new items from completely novel semantic categories. There was no significant interaction between group and item category.

<u>Functional fMRI results:</u> New items from old semantic categories which had previously been named in English showed greater activation than new items from new categories but the results also revealed significant differences between monolinguals and bilinguals. Bilinguals showed greater activation than monolinguals in the right frontal pole, bilateral anterior cingulate, right superior parietal cortex, and bilateral precuneus cortex which extended into bilateral posterior cingulate. There were no regions in which monolinguals had more activation than bilinguals in this comparison[4] (Table 5 and Figure 8).

Correlations with proficiency

To determine how proficiency in the L2 modulated performance, a set of correlational analyses was performed for the data on Runs 1 and 2 and then for the data from Runs 3–8. The first of these analyses showed that for bilinguals, there were positive correlations between L2 proficiency and functional activation in Run 1 in the bilateral frontal pole, right inferior frontal gyrus, and bilateral occipital cortices (Table 6; Figure 9).

Moreover, although there were no significant correlations between L2 proficiency and functional activation while naming pictures in Spanish (in Run 2), there were positive correlations between L2 proficiency and brain activation naming in English (Runs 3–8) after naming in Spanish in the right anterior temporal cortex, right inferior frontal gyrus which extended into insular cortex, and right post-central gyrus (Table 7; Figure 10).

Discussion

Previous research has demonstrated that bilingual speakers engage language specific and domain general neural networks during language processing to monitor and control their languages (Abutalebi & Green, 2007; Green & Abutalebi, 2013). The hypothesis is that bilinguals need to temporarily suppress the more dominant language in order to achieve successful speech production in the L2 (e.g., Green, 1998; Levy et al., 2007; Linck, Kroll & Sunderman, 2009; Philipp et al., 2007). Past fMRI evidence suggests that bilinguals engage a wide neural network that encompasses cortical and subcortical structures (including ACC/pre-SMA, bilateral inferior frontal cortices, and the basal ganglia with caudate and putamen) to enable language monitoring and control. A number of behavioral and neuroimaging

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[4]An additional table reporting significant functional activation contrasting new items from old semantic categories which had previously been named in English to new items from new categories for the two groups separately are reported in Appendix A (table B).

experiments support this view (for a recent review see Li, Legault & Litcofsky, 2014). Although neural evidence regarding the scope of this control network is still emerging, preliminary accounts suggest that control over the strongest language is likely to extend beyond local control of single lexical items (Branzi et al., 2016; Guo et al., 2011; Misra et al., 2012; Van Assche et al., 2013). Thus, the primary goal of the present study was to further examine the scope of the language control network – to evaluate whether it is specific to the lexical item (i.e., local control), or whether it extends more broadly to the semantic system or even across the entire language. We were also interested how proficiency in the L2 may modulate the language control network.

Functional activation in Run 1 and Run 2: Bilingualism as a modulator of the L1's functional network

In line with previous evidence (e.g., Parker Jones et al., 2012) our results reveal that even before naming in the L2, bilinguals recruit a wider functional network than monolinguals, that includes language control regions such as bilateral occipital cortex, bilateral fusiform and inferior temporal cortex, bilateral inferior parietal cortex, bilateral putamen, and bilateral anterior cingulate. Importantly, the anterior cingulate has been deemed important for attention, conflict monitoring, and error detection (Abutalebi & Green, 2007), while basal ganglia regions are important for language planning and language selection. This result is important because it converges with evidence showing that bilinguals' both languages are constantly coactivated, even when intending to speak one language alone, and need to be regulated even when speaking in the L1 (Costa, 2005; Kroll et al., 2006, Román et al., 2015). Importantly, recent data has reported the activation of similar domain general regions during response inhibition in a go-no-go naming task in monolinguals (Zhang et al., 2018), suggesting an active role of these areas for language control. The present results highlight the way that bilingualism may change the underlying functional network that is recruited during native language processing. The evidence that bilinguals may engage different brain areas than monolinguals even when processing the native language, corroborates data showing long term structural changes in gray and white matter connectivity, even when the L2 is acquired relatively late in life (Rossi et al., 2017; Pliatsikas, Moschopoulou & Saddy, 2015; Pliatsikas et al., 2017; Olsen et al., 2015).

A possible alternative interpretation of the present results is that bilingual participants were aware that the task would require them switching into their L2 at some point in the study. As such, the observed effect could have been the result of preemptive activation of the L2, even before the L2 was spoken. Parker Jones et al. (2012) compared functional activation during a picture naming and a reading aloud task for bilinguals when they were tested in a single language context, in their native language or their second language. In contrast to the present study, they tested the two languages on different days. Their results revealed that bilinguals had increased activation in left frontal and temporal regions relative to monolinguals when they were naming in their native language, suggesting that even when bilinguals are placed in a single language context, their functional network still differs from monolinguals'.

Results for functional activation in Run 2 revealed, not surprisingly, that bilinguals' naming in the L2 elicited greater activation in areas identified as being important for language

processing, including left lateral occipital cortex, implicated in sublexical processing (Levy et al., 2009), and also areas that are critical for language selection and general control, such as left caudate (e.g., Abutalebi & Green, 2007; Branzi et al., 2016), the right putamen (Marian et al., 2017), and left middle frontal gyrus, implicated in bilingual language control during language switching (Luk et al., 2011) supporting previous evidence showing that processing in the L2 might recruit larger networks, suggesting overall greater effort (Hasegawa et al., 2002).

Identifying hierarchical levels of bilingual language control (comparing different types of items within Runs 3–8).

This study was specifically designed to test predictions about the scope of bilingual language control, and to further inform neural models of bilingual language processing (Abutalebi & Green, 2007; Green & Abutalebi, 2013). It was hypothesized that if bilinguals need to exert control on their native language during L2 production beyond the single word level, the activation of the areas implicated in the bilingual functional control network should be observed for local control, for the control at the broader semantic level, and also at the level of the whole language. The present results suggest that bilinguals recruit a wide network of areas for bilingual language control, including cortical and subcortical structures (such as the caudate and putamen).

For local control, the results in the present study show that when naming the identical concepts in English during Runs 3–8 after having spoken the L2, bilinguals show greater activation than monolinguals in right precentral gyrus, and central cingulate gyrus. The observed functional pattern of functional activation replicates the effects reported by Guo et al. (2011) when bilinguals switched from naming in the L1 after naming in the L2. In addition, the present results also highlight the activation of areas previously implicated in bilingual control such as the cingulate gyrus, indicating that bilinguals engage areas involved in active conflict monitoring when naming words that were named before switching into the L2. Moreover, the right precentral gyrus has recently been identified as important for attentional demand required in language processing (Sabri, Binder, Deasi, Medler, Leitl & Liebenthal, 2008; Luk et al., 2011). For the same comparison, monolinguals instead showed greater activation in the frontal pole and in left precentral gyrus. Left precentral gyrus is implicated in specific top-down control for language processing more specifically. These findings thus suggest that bilinguals engage neural areas that have been specifically identified with bilingual language inhibitory control (anterior cingulate), and attentional demands for local control.

The focal question we hoped to answer was whether engagement of the control network would extend beyond local control to the broader semantic category. The results demonstrate that bilinguals elicited greater activation than monolinguals in middle, right and left cingulate gyrus, and left precuneus while naming new items in English (in Runs 3–8) which were drawn from semantic categories that were previously named in Run 1 before naming in Spanish. The same comparison for monolinguals did not yield any significant differences in activation. These results suggest that bilinguals (but not monolinguals) continue to engage a neural network dedicated to language control (i.e., cingulate cortex) even for words that

were not previously named, suggesting that control processes go beyond the local item level and expand to the broader semantic category. Importantly, cingulate cortex is implicated in attention, conflict monitoring and attentional processes (Abutalebi & Green, 2007).

Finally, the present results also show that bilinguals (but not monolinguals) activate a wide control network for completely novel items, engaging bilateral caudate, putamen, anterior cingulate and anterior temporal lobe. Basal ganglia (with caudate and putamen) play a crucial role for language selection, language and planning (Abutalebi & Green, 2007), with the caudate playing a specific role in monitoring verbal interference (Abutalebi et al., 2008; Ali, Green, Kherif, Devlin, & Price, 2010). These data suggest that bilinguals need to temporarily control and inhibit the whole language globally, beyond the single word level, and beyond specific semantic categories. The results are also partly in line with the dual model of control proposed by Branzi et al. (2016), that posits that the control system is hierarchically organized with the dorsal anterior cingulate cortex being important for local control, and prefrontal and inferior parietal areas and the caudate monitoring both local and global control.

Overall, the current results demonstrate that when bilinguals engage in speaking each of their two languages, and need to switch between languages, they recruit a wide network of areas that have been previously identified as important for bilingual language control (Abutalebi & Green, 2007, Abutalebi et al., 2008; Abutalebi et al., 2013; Luk et al., 2011). Crucially, this network is active for local control, and spreads globally to the entire language.

L2 proficiency as a modulator of bilingual language processing functional networks

A second aspect of interest was to investigate how the functional network that is recruited during bilingual language processing might be modulated by L2 proficiency. We hypothesized that if recruitment of neural areas dedicated to cognitive control depends on the relative proficiency in the L2 (i.e., Bartolotti et al., 2016; Parker Jones et al., 2012; Van Assche et al., 2013), a correlation between proficiency and activation in neural areas should be observed. The results showed that there was a positive correlation between functional activation and L2 proficiency in Run 1 when participants named in English, even before naming in Spanish in bilateral frontal pole, right inferior frontal gyrus, and bilateral occipital cortices. In addition, a positive correlation was found between L2 proficiency and functional activation while naming in English (in Runs 3–8) in the right anterior temporal cortex, right inferior frontal gyrus, and right post-central gyrus. Importantly, the right inferior frontal cortex has been identified as part of cortical-subcortical connection to the thalamus that is involved in in language control by detecting salient cues (Green & Abutalebi, 2013), and occipital cortices (BA 17, 18, and 19) have been described as being part of the ventral pathway (inferior frontal occipital fasciculus –IFOF-) which connects the language areas, and which has been claimed to be important for word recognition (López-Barroso et al., 2013), and semantic processing (Duffau, 2008; Duffau et al., 2009). If L2 proficiency is a proxy for L2 overall activation, these results might be taken to suggest that greater L2 activation requires greater activation of control areas. This interpretation would be particularly relevant for the results showing a positive correlation between proficiency in the L2 and functional activation in Run 1, suggesting that higher L2 proficiencies require more

L1 control, even before the L2 is spoken. This result is somehow opposite to the general assumption made in the literature, i.e., that control is more needed in the beginning stages of L2 learning but decreases as proficiency increases. Instead, this data suggest that a certain level of control might be always needed even at higher proficiency levels.

Conclusion

The present study contributes important new data to the existing literature on the neural mechanisms underlying bilingual language control. First, in line with previous evidence, we show that bilinguals engaged a wide functional control network during bilingual language production, and that this functional network was activated for local as well global control of the whole language. We demonstrate, for the first time, how this control network is hierarchically organized to control the single lexical level, the broader semantic category, and beyond to the whole lexicon, showing that different portions of the broader network come online for different control needs. Crucially, we also demonstrate that proficiency in the L2 is an important factor that is likely to modulate bilingual language control processes. The present results add to growing evidence showing that bilingualism has the potential to shape the neural substrates underlying native language processing, making bilingualism a true testbed to study neural plasticity and its consequences across the life-span (Gold et al., 2013).

Acknowledgments

Appendix A:: Language History Questionnaire

Language History Questionnaire

This questionnaire is designed to give us a better understanding of your experience with other languages. We ask that you be as accurate as thorough as possible when answering the following questions.

1. Gender

    ❑   Male

    ❑   Female

2. Age:

3. Do you have any known visual or hearing problems (corrected or uncorrected)?

    ❑   Yes

    ❑   No

4. Native Country

    ❑   United States

    ❑ Other _____

5. Native Language

   ❑ English

   ❑ Other _____

6. Language(s) spoken at home (Please check all that apply).

   ❑ English

   ❑ Spanish

   ❑ German

   ❑ Other [Please explain:

     _____

  If ENGLISH is your Native Language, please RATE yourself:

  ***If English is <u>NOT</u> your Native Language, please contact Experimenter for further instructions.

7. Please rate your English reading proficiency. (1=not literate and 10 = very literate)

   ❑ 1

   ❑ 2

   ❑ 3

   ❑ 4

   ❑ 5

   ❑ 6

   ❑ 7

   ❑ 8

   ❑ 9

   ❑ 10

8. Please rate your English writing proficiency. (1=not literate and 10=very literate)

   ❑ 1

   ❑ 2

   ❑ 3

   ❑ 4

   ❑ 5

   ❑ 6

   ❑ 7

❑ 8

❑ 9

❑ 10

9. Please rate your English speaking ability. (1=not fluent and 10=very fluent)

❑ 1

❑ 2

❑ 3

❑ 4

❑ 5

❑ 6

❑ 7

❑ 8

❑ 9

❑ 10

10. Please rate your English speech comprehension ability. (1=unable to understand conversation and 10=perfectly able to understand)

❑ 1

❑ 2

❑ 3

❑ 4

❑ 5

❑ 6

❑ 7

❑ 8

❑ 9

❑ 10

The next section of the questionnaire deals with your second language learning experience.

11. Have you studied any second language?

❑ No → **If NO, please go to question #19**

❑ Yes

If YES, where and when? Please check all that apply and indicate length of study.

- ❏ Home Language: _____
- ❏ Since Age ( )

Elementary School Language: _____

- ❏ ( ) year(s)

Middle School Language: _ _____

- ❏ ( ) year(s)

High School Language: _ _____

- ❏ 1 year
- ❏ 2 years
- ❏ 3 years

College Language:

- ❏ Have not studied a second language in college
- ❏ 1–2 semesters
- ❏ 3–4 semesters
- ❏ 5–6 semesters
- ❏ 8+ semesters

12. If you are taking/have taken any second language at college, please answer the following question. Are you: (Please check all that apply.)

- ❏ Taking a second language for a requirement but interested in being a major or minor.
- ❏ A second language minor
- ❏ A second language major
- ❏ A second language graduate student
- ❏ Other [please explain _____]

13. Have you studied / lived abroad?

- ❏ Yes
- ❏ No

If Yes, where and when did you study, for how long, and what language did you speak?

Country	Approx. dates	Length of Stay	Language

The next section asks you to rate your skills in your primary second language.

14. Please rate your second language reading proficiency. (1=not literate and 10=very literate)

- ❏ 1
- ❏ 2
- ❏ 3
- ❏ 4
- ❏ 5
- ❏ 6
- ❏ 7
- ❏ 8
- ❏ 9
- ❏ 10

15. Please rate your second language writing proficiency. (1=not literate and 10=very literate)

- ❏ 1
- ❏ 2
- ❏ 3
- ❏ 4
- ❏ 5
- ❏ 6
- ❏ 7
- ❏ 8
- ❏ 9
- ❏ 10

16. Please rate your second language speaking ability. (1=not fluent and 10=very fluent)

- ❏ 1
- ❏ 2
- ❏ 3

- ❑ 4
- ❑ 5
- ❑ 6
- ❑ 7
- ❑ 8
- ❑ 9
- ❑ 10

17. Please rate your second language speech comprehension ability. (1=unable to understand conversation and 10=perfectly able to understand)

- ❑ 1
- ❑ 2
- ❑ 3
- ❑ 4
- ❑ 5
- ❑ 6
- ❑ 7
- ❑ 8
- ❑ 9
- ❑ 10

18. In my second language classes I get:

- ❑ Mostly A's
- ❑ Mostly A's and B's
- ❑ Mostly B's
- ❑ Mostly B's and C's
- ❑ Mostly C's

19. If you speak or have studied more than one second language, please explain about your additional language experience (i.e. years, level of proficiency, etc.)

Thank you for your participation!

Additional Figures
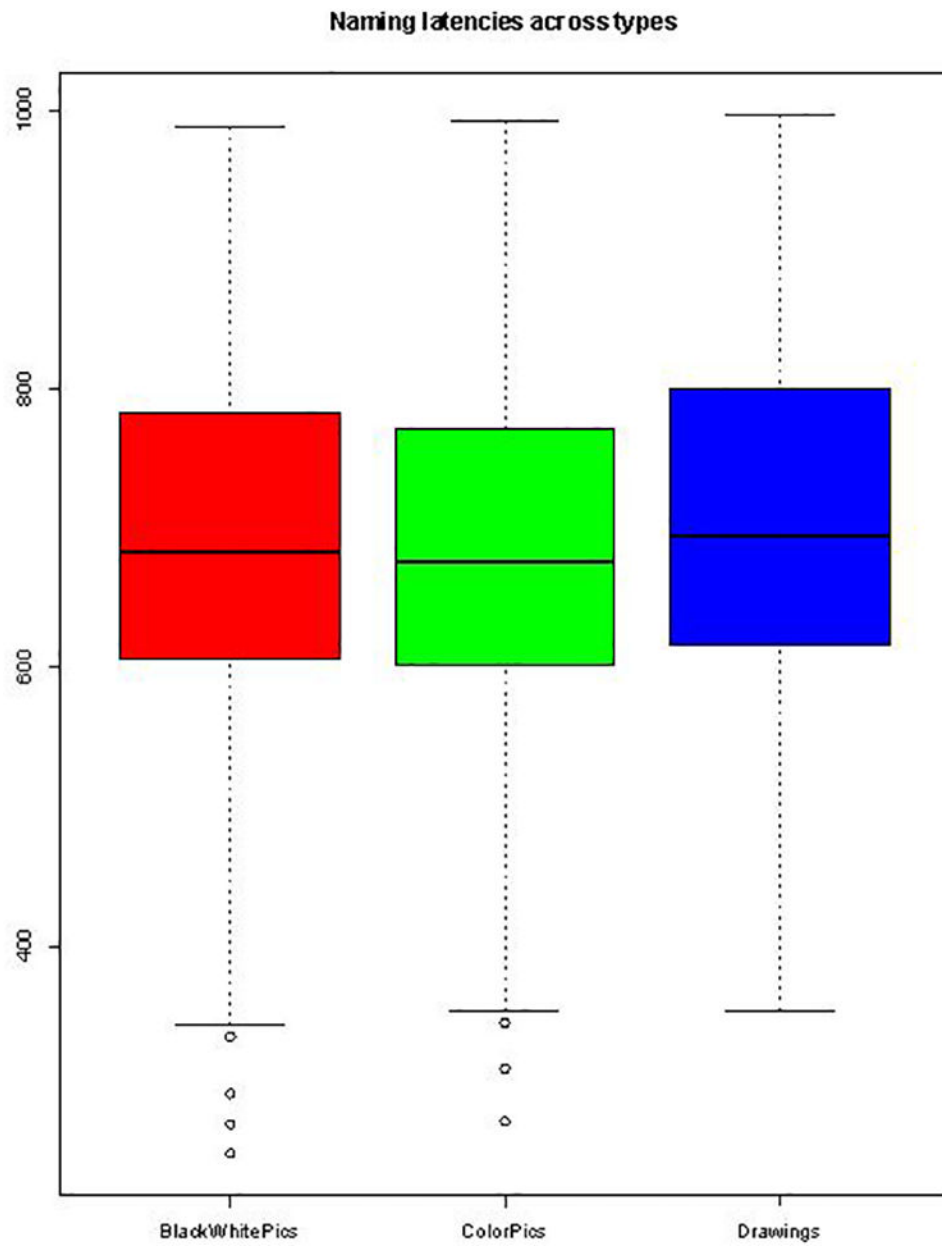
Figure A:
Naming latencies colored pictures, black and white pictures, and black and white drawings.

Additional activation tables

Table A:

Functional activation results contrasting activations for items that had previously been named in English in Run 3–8 > same identical items named in Run 1 for Bilinguals and Monolinguals separately.

	Hemisphere	Coordinates			voxels	z value
		x	y	z		
Bilinguals						
Middle Temporal Gyrus	Right	46	−56	6	15858	7.76
Lateral Occipital Cortex	Right	44	−60	10		
Precuneous Cortex	Left	−14	−64	26		
Lateral Occipital Cortex	Left	−42	−68	6		
Lateral Occipital Cortex	Right	44	−70	−6		
Precentral Gyrus	Left	−6	−26	54		
Frontal Pole	Right	30	36	36	3240	5.5
Middle Frontal Gyrus	Right	32	28	32		
Inferior Frontal Gyrus	Right	32	20	20		
Frontal Pole	Right	26	40	−6		
Middle Frontal Gyrus	Right	32	32	36		
Frontal Pole	Right	28	46	10		
Cingulate Gyrus	Left	−18	30	14	1812	4.29
Middle Frontal Gyrus	Left	−22	34	14		
Middle Frontal Gyrus	Left	−26	34	14		
Middle Frontal Gyrus	Left	−26	32	14		
Superior Frontal Gyrus	Left	−20	30	30		
Middle Frontal Gyrus	Left	−24	24	34		
Monolinguals						
Cingulate Gyrus	Right	8	28	10	10955	6.62
Paracingulate Gyrus	Right	6	48	10		
Middle Frontal Gyrus	Left	−38	14	56		
Superior Frontal Gyrus	Left	−22	32	46		
Middle Frontal Gyrus	Left	−46	16	48		
Superior Frontal Gyrus	Left	−20	36	44		
Lateral Occipital Cortex	Left	−24	−86	18	9159	6.68
Precentral Gyrus	Right	12	−32	68		
Occipital Pole	Left	−10	−92	18		
Precentral Gyrus	Right	6	−26	58		
Precentral Gyrus	Left	−4	−32	58		
Precentral Gyrus	Right	6	−30	62		
Lateral Occipital Cortex	Right	36	−86	8	3061	6.29

	Hemisphere	Coordinates			voxels	z value
		x	y	z		
Lateral Occipital Cortex	Right	34	−84	6		
Lateral occipital Cortex	Right	30	−88	0		
Lateral Occipital Cortex	Right	34	−84	10		
Lateral Occipital Cortex	Right	40	−86	−6		
Occipital Pole	Right	22	−90	14		

Table B:

Functional activation results for new items from old semantic categories which had previously been named in English showing greater activation than new items from new categories for bilinguals and monolinguals.

	Hemisphere	Coordinates			Voxels	z value
		x	y	z		
Bilinguals						
Occipital Pole	Middle	0	−98	10	2044	3.94
Occipital Pole	Right	16	−92	10		
Occipital Pole	Middle	0	−98	6		
Occipital Pole	Right	4	−96	10		
Occipital Pole	Right	10	−96	6		
Occipital Pole	Right	16	−96	12		
Monolinguals						
Occipital Pole	Right	10	−96	−2	2371	3.93
Occipital Fusiform Gyrus	Right	44	−66	−28		
Temporal Occipital Fusiform Cortex	Right	36	−60	−24		
Temporal Occipital Fusiform Cortex	Right	44	−60	−18		
Occipital Fusiform Gyrus	Right	38	−66	−22		
Lateral Occipital Cortex	Right	44	−72	−24		
Temporal Occipital Fusiform	Left	−40	−64	−20	1178	3.6
Temporal Occipital Fusiform	Left	−36	−64	−22		
Temporal Occipital Fusiform	Left	−40	−54	−16		
Lateral Occipital Cortex	Left	−44	−82	−28		
Inferior Temporal Gyrus	Left	−48	−60	−22		
Temporal Occipital Fusiform	Left	−44	−56	−24		

References

Abutalebi J, & Green D (2007). Bilingual language production: The neurocognition of language representation and control. Journal of Neurolinguistics, 20(3), 242–275. 10.1016/j.jneuroling. 2006.10.003

Abutalebi J, Annoni JM, Zimine I, Pegna AJ, Seghier ML, Lee-Jahnke H, & Khateb A (2008). Language control and lexical competition in bilinguals: an event-related fMRI study. Cerebral Cortex, 18(7), 1496–1505. 10.1093/cercor/bhm182 [PubMed: 17947346]

Abutalebi J, Della Rosa PA, Ding G, Weeks B, Costa A, & Green DW (2013). Language Proficiency Modulates the Engagement of Cognitive Control Areas in Multilinguals. Cortex: a Journal Devoted to the Study of the Nervous System and Behavior, 49, 905–911. 10.1016/j.cortex.2012.08.018 [PubMed: 23021069]

Abutalebi J, Della Rosa PA, Green DW, Hernandez M, Scifo P, Keim R, & Costa A (2011). Bilingualism tunes the anterior cingulate cortex for conflict monitoring. Cerebral cortex, 22(9), 2076–2086. 10.1093/cercor/bhr287 [PubMed: 22038906]

Abutalebi J, Miozzo A, & Cappa SF (2000). Do subcortical structures control 'language selection' in polyglots? Evidence from pathological language mixing. Neurocase, 6(1), 51–56.

Ali N, Green DW, Kherif F, Devlin JT, & Price CJ (2010). The role of the left head of caudate in suppressing irrelevant words. Journal of Cognitive Neuroscience, 22(10), 2369–2386. 10.1162/jocn. 2009.21352 [PubMed: 19803688]

Bartolotti J, Bradley K, Hernandez AE, & Marian V (2017). Neural signatures of second language learning and control. Neuropsychologia, 98, 130–138. 10.1016/j.neuropsychologia.2016.04.007 [PubMed: 27068064]

Branzi FM, Della Rosa PA, Canini M, Costa A, & Abutalebi J (2016). Language control in bilinguals: monitoring and response selection. Cerebral Cortex, 26(6), 2367–2380. 10.1093/cercor/bhv052 [PubMed: 25838037]

Christoffels IK, Firk C, & Schiller NO (2007). Bilingual language control: An event-related brain potential study. Brain Research, 1147, 192–208. 10.1016/j.brainres.2007.01.137 [PubMed: 17391649]

Costa A (2005). Lexical access in bilingual production In Kroll JF & De Groot AMB (Eds.), Handbook of bilingualism: Psycholinguistic approaches (pp. 308–325). New York: Oxford University Press ISBN 0-19-515177-1

Crocker L, & Algina J (1986). Introduction to classical and modern Test Theory. Fort Worth, TX: Holt, Rinehart and Winston ISBN 0030616344

Dale AM (1999). Optimal experimental design for event-related fMRI. Human Brain Mapping, 8, 109–114. 10.1002/(SICI)1097-0193(1999)8:2/3<109::AID-HBM7>3.0.CO;2-W [PubMed: 10524601]

Duffau H (2008). The anatomo-functional connectivity of language revisited: new insights provided by electrostimulation and tractography. Neuropsychologia, 46(4), 927–934. 10.1016/j.neuropsychologia.2007.10.025 [PubMed: 18093622]

Duffau H, Gatignol P, Moritz-Gasser S, & Mandonnet E (2009). Is the left uncinate fasciculus essential for language? Journal of neurology, 256(3), 382–389. 10.1007/s00415-009-0053-9 [PubMed: 19271103]

Gold BT, Kim C, Johnson NF, Kryscio RJ, & Smith CD (2013). Lifelong Bilingualism Maintains Neural Efficiency for Cognitive Control in Aging. Journal of Neuroscience, 33, 387–396. 10.1523/JNEUROSCI.3837-12.2013 [PubMed: 23303919]

Green DW (1998). Mental control of the bilingual lexico-semantic system. Bilingualism: Language and Cognition, 1(02), 67–81. 10.1017/S1366728998000133

Green DW, & Abutalebi J (2013). Language control in bilinguals: The adaptive control hypothesis. Journal of Cognitive Psychology, 25(5), 515–530. 10.1080/20445911.2013.796377 [PubMed: 25077013]

Greve DN, & Fischl B (2009). Accurate and robust brain image alignment using boundary-based registration. Neuroimage, 48(1), 63–72. 10.1016/j.neuroimage.2009.06.060 [PubMed: 19573611]

Guo T, Liu H, Misra M, & Kroll JF (2011). Local and global inhibition in bilingual word production: fMRI evidence from Chinese–English bilinguals. NeuroImage, 56(4), 2300–2309. 10.1016/j.neuroimage.2011.03.049 [PubMed: 21440072]

Hayasaka S, & Nichols TE (2003). Validating cluster size inference: random field and permutation methods. Neuroimage, 20(4), 2343–2356. doi:10.1016/j.neuroimage.2003.08.003 [PubMed: 14683734]

Hasegawa M, Carpenter PA, & Just MA (2002). An fMRI study of bilingual sentence comprehension and workload. Neuroimage, 15(3), 647–660. doi:10.1006/nimg.2001.1001 [PubMed: 11848708]

Jackson GM, Swainson R, Cunnington R, & Jackson SR (2001). ERP correlates of executive control during repeated language switching. Bilingualism: Language and Cognition, 4, 169–178. 10.1017/S1366728901000268

Jenkinson M, & Smith S (2001). A global optimisation method for robust affine registration of brain images. Medical image analysis, 5(2), 143–156. 10.1016/S1361-8415(01)00036-6 [PubMed: 11516708]

Jenkinson M, Bannister P, Brady M, & Smith S (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. Neuroimage, 17(2), 825–841. 10.1016/S1053-8119(02)91132-8 [PubMed: 12377157]

Keijzer M (2014). Changes in Neural Activation Patterns and Brain Anatomy as a Function of Non-Pathological First Language Attrition. Journal of Neurological Disorders, 2(4), 171–177. doi: 10.4172/2329-6895.1000171

Kootstra GJ, Van Hell JG, & Dijkstra T (2010). Syntactic alignment and shared word order in codeswitched sentence production: Evidence from bilingual monologue and dialogue. Journal of Memory and Language, 63, 210–231. doi:10.1016/j.jml.2010.03.006

Kriegeskorte N, Simmons WK, Bellgowan PS, & Baker CI (2009). Circular analysis in systems neuroscience: the dangers of double dipping. Nature neuroscience, 12(5), 535–540. 10.1038/nn. 2303 [PubMed: 19396166]

Kroll JF, Bobb S, & Wodniekca Z (2006). Language selectivity is the exception, not the rule: Arguments against a fixed locus of language selection in bilingual speech. Bilingualism: Language and Cognition, 9(2), 119–135. 10.1017/S1366728906002483

Kroll JF, Bobb SC, Misra M, & Guo T (2008). Language selection in bilingual speech: Evidence for inhibitory processes. Acta psychologica, 128(3), 416–430. 10.1016/j.actpsy.2008.02.001 [PubMed: 18358449]

Levy BJ, Mcveigh ND, Marful A, & Anderson MC (2007). Inhibiting Your Native Language: the role of retrieval-induced forgetting during second-language acquisition. Psychological Science, 18(1), 29–34. 10.1111/j.1467-9280.2007.01844.x [PubMed: 17362374]

Levy J, Pernet C, Treserras S, Boulanouar K, Aubry F, Démonet JF, & Celsis P (2009). Testing for the dual-route cascade reading model in the brain: an fMRI effective connectivity account of an efficient reading style. PloS one, 4(8), e6675 10.1371/journal.pone.0006675 [PubMed: 19688099]

Li P, Legault J, and Litcofsky KA (2014). Neuroplasticity as a function of second language learning: anatomical changes in the Human brain. Cortex 58, 301–324. 10.1016/j.cortex.2014.05.001 [PubMed: 24996640]

Linck JA, Kroll JF, & Sunderman G (2009). Losing access to the native language while immersed in a second language: Evidence for the role of inhibition in second-language learning. Psychological Science, 20(12), 1507–1515. 10.1111/j.1467-9280.2009.02480.x [PubMed: 19906121]

Luk G, Green DW, Abutalebi J, & Grady C (2011). Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. Language and cognitive processes, 27(10), 1479–1488. 10.1080/01690965.2011.613209 [PubMed: 24795491]

Marian V, Bartolotti J, Rochanavibhata S, Bradley K, & Hernandez AE (2017). Bilingual Cortical Control of Between-and Within-Language Competition. Scientific reports, 7(1), 11763 10.1038/s41598-017-12116-w [PubMed: 28924215]

McMurray B, Samelson VM, Lee SH, & Tomblin JB (2010). Individual differences in online spoken word recognition: Implications for SLI. Cognitive Psychology, 60(1), 1–39. 10.1016/j.cogpsych.2009.06.003 [PubMed: 19836014]

Ministry of Education, Culture, and Sport of Spain (2006). Diploma de Español como Lengua Extranjera (Diploma of Spanish as a Second Language Examination). Retrieved from http://www.dele.org/

Misra M, Guo T, Bobb SC, & Kroll JF (2012). When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. Journal of Memory and language, 67(1), 224–237. 10.1016/j.jml.2012.05.001

Myers-Scotton C (2006). Natural codeswitching knocks on the laboratory door. Bilingualism: Language and Cognition, 9(2), 203–212. 10.1017/S1366728906002549

Olsen RK, Pangelinan MM, Bogulski C, Chakravarty MM, Luk G, Grady CL, & Bialystok E (2015). The effect of lifelong bilingualism on regional grey and white matter volume. Brain research, 1612, 128–139. 10.1016/j.brainres.2015.02.034 [PubMed: 25725380]

Parker Jones   , Green DW, Grogan A, Pliatsikas C, Filippopolitis K, Ali N, & Seghier ML (2012). Where, when and why brain activation differs for bilinguals and monolinguals during picture naming and reading aloud. Cerebral Cortex, 22(4), 892–902. 10.1093/cercor/bhr161 [PubMed: 21705392]

Philipp A, Gade M, & Koch I (2007). Inhibitory processes in language switching: Evidence from switching language-defined response sets. European Journal of Cognitive Psychology, 19, 395–416. 10.1080/09541440600758812

Pivneva I, Palmer C, & Titone D (2012). Inhibitory control and L2 proficiency modulate bilingual language production: Evidence from spontaneous monologue and dialogue speech. Frontiers in Psychology, 3, 57 10.3389/fpsyg.2012.00057 [PubMed: 22438846]

Pliatsikas C, & Luk G (2016). Executive control in bilinguals: a concise review on fMRI studies. Bilingualism: Language and Cognition, 19(4), 699–705. 10.1017/S1366728916000249

Pliatsikas C, DeLuca V, Moschopoulou E, & Saddy JD (2017). Immersive bilingualism reshapes the core of the brain. Brain Structure and Function, 222(4), 1785–1795. 10.1007/s00429-016-1307-9 [PubMed: 27678394]

Pliatsikas C, Moschopoulou E, & Saddy JD (2015). The effects of bilingualism on the white matter structure of the brain. Proceedings of the National Academy of Sciences, 112(5), 1334–1337. 10.1073/pnas.1414183112

Reverberi C, Kuhlen AK, Seyed-Allaei S, Greulich RS, Costa A, Abutalebi J, & Haynes J-D (2018). The neural basis of free language choice in bilingual speakers: Disentangling language choice and language execution. NeuroImage, 177, 108–116. 10.1016/j.neuroimage.2018.05.025 [PubMed: 29753107]

Román P, González J, Ventura-Campos N, Rodríguez-Pujadas A, Sanjuán A, & Ávila C (2015). Neural differences between monolinguals and early bilinguals in their native language during comprehension. Brain and language, 150, 80–89. 10.1016/j.bandl.2015.07.011 [PubMed: 26340683]

Rossi E, Cheng H, Kroll JF, Diaz MT, & Newman SD (2017). Changes in White-Matter Connectivity in Late Second Language Learners: Evidence from Diffusion Tensor Imaging. Frontiers in psychology, 8, 2040 10.3389/fpsyg.2017.02040 [PubMed: 29209263]

Sabri M, Binder JR, Desai R, Medler DA, Leitl MD, & Liebenthal E (2008). Attentional and linguistic interactions in speech perception. Neuroimage, 39(3), 1444–1456. 10.1016/j.neuroimage.2007.09.052 [PubMed: 17996463]

Smith SM, Jenkinson M, Johansen-Berg H, Rueckert D, Nichols TE, Mackay CE, Watkins KE, Ciccarelli O, Cader MZ, Matthews PM, Behrens TE (2006). Tract-based spatial statistics: voxelwise analysis of multi-subject diffusion data. Neuroimage 31, 1487–1505. 10.1016/j.neuroimage.2006.02.024 [PubMed: 16624579]

Snodgrass J, Vanderwart M. (1980). A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. Journal of Experimental Psychology Human, 6(2), 174–215. 10.1037/0278-7393.6.2.174

Tettamanti M, Alkhadit H, Moros A, Weniger D, Perani D, Kolliast S, & Fazio F (2001). Neural Correlates of Learning New Grammatical Rules: a fMRI Study. Language, 12(6), 2001–2001. 10.1016/S1053-8119(02)91201-2

Stocco A, & Prat CS (2014). Bilingualism trains specific brain circuits involved in flexible rule selection and application. Brain and language, 137, 50–61. 10.1016/j.bandl.2014.07.005 [PubMed: 25156160]

Van Assche E, Duyck W, & Gollan TH (2013). Whole-language and item-specific control in bilingual language production. Journal of Experimental Psychology: Learning, Memory, and Cognition, 39(6), 1781 10.1037/a0032859

Williams JT, Darcy I, & Newman SD (2016). Modality-specific processing precedes amodal linguistic processing during L2 sign language acquisition: A longitudinal study. Cortex, 75(April 2016), 56–67. 10.1016/j.cortex.2015.11.015 [PubMed: 26720258]

Woolrich MW, Jbabdi S, Patenaude B, Chappell M, Makni S, Behrens T, & Smith SM (2009). Bayesian analysis of neuroimaging data in FSL. Neuroimage, 45(1), S173–S186. 10.1016/j.neuroimage.2008.10.055 [PubMed: 19059349]

Worsley K (2001). Statistical analysis of activation images In Jezzard P, Matthews PM, & Smith SM (Eds.), Functional Magnetic Resonance Imaging: An introduction to methods (pp. 251–270). Oxford, England: Oxford University Press.

Zhang H, Eppes A, Beatty-Martínez A, Navarro-Torres C, & Diaz MT (2018). Task difficulty modulates brain-behavior correlations in language production and cognitive control: Behavioral and fMRI evidence from a phonological go/no-go picture-naming paradigm. Cognitive, Affective, & Behavioral Neuroscience, 1–18. 10.3758/s13415-018-0616-2 Task

Zou L, Abutalebi J, Zinszer B, Yan X, Shu H, Peng D, & Ding G (2012). Second language experience modulates functional brain network for the native language production in bimodal bilinguals. NeuroImage, 62(3), 1367–1375. 10.1016/j.neuroimage.2012.05.062 [PubMed: 22658973]
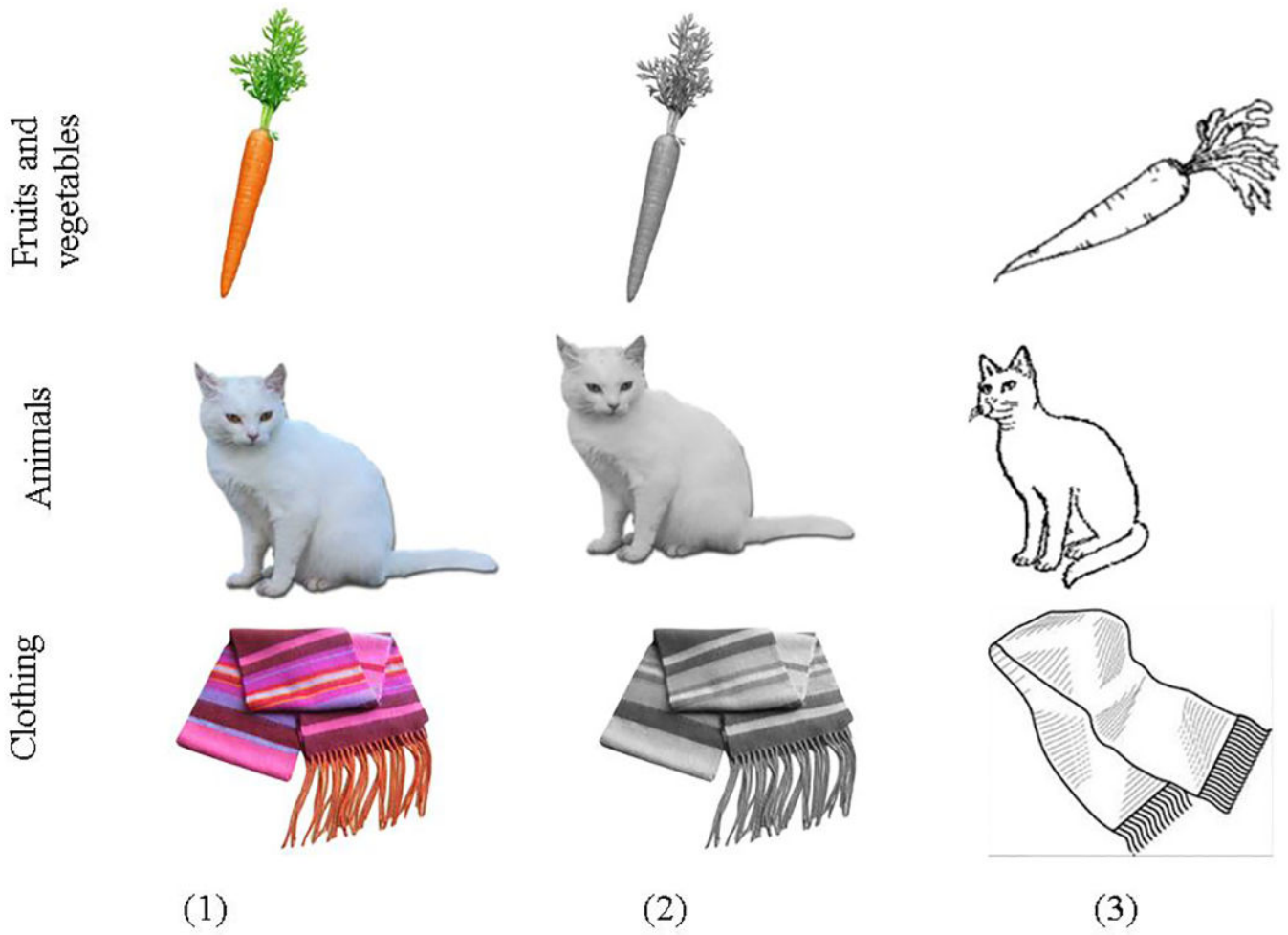
Figure 1:
Examples of pictures used in the task for three semantic categories. Items were presented as colored pictures (1), black and white pictures (2) and line drawings (3).
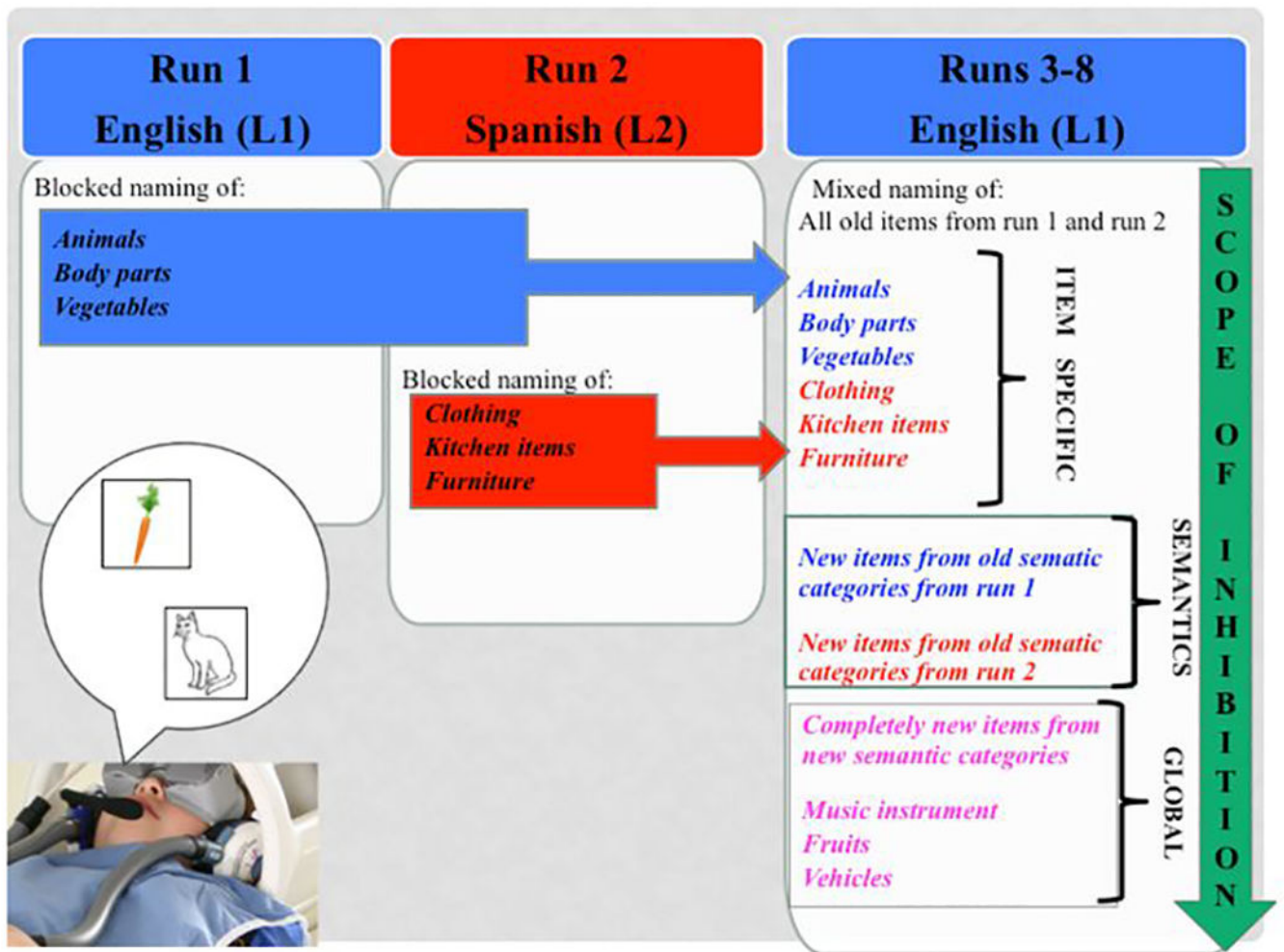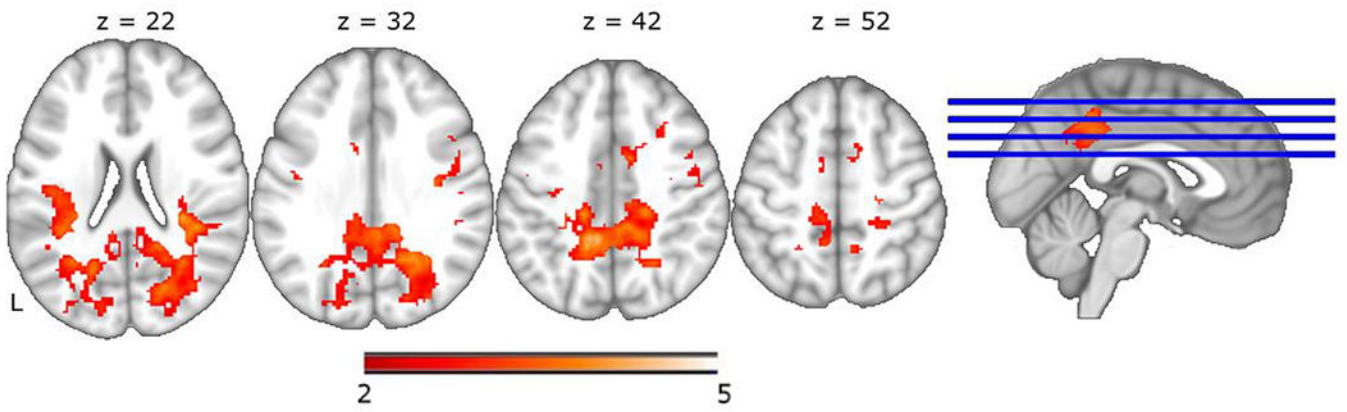
Figure 2:
Experimental design for bilinguals (monolinguals completed the same protocol in English only).
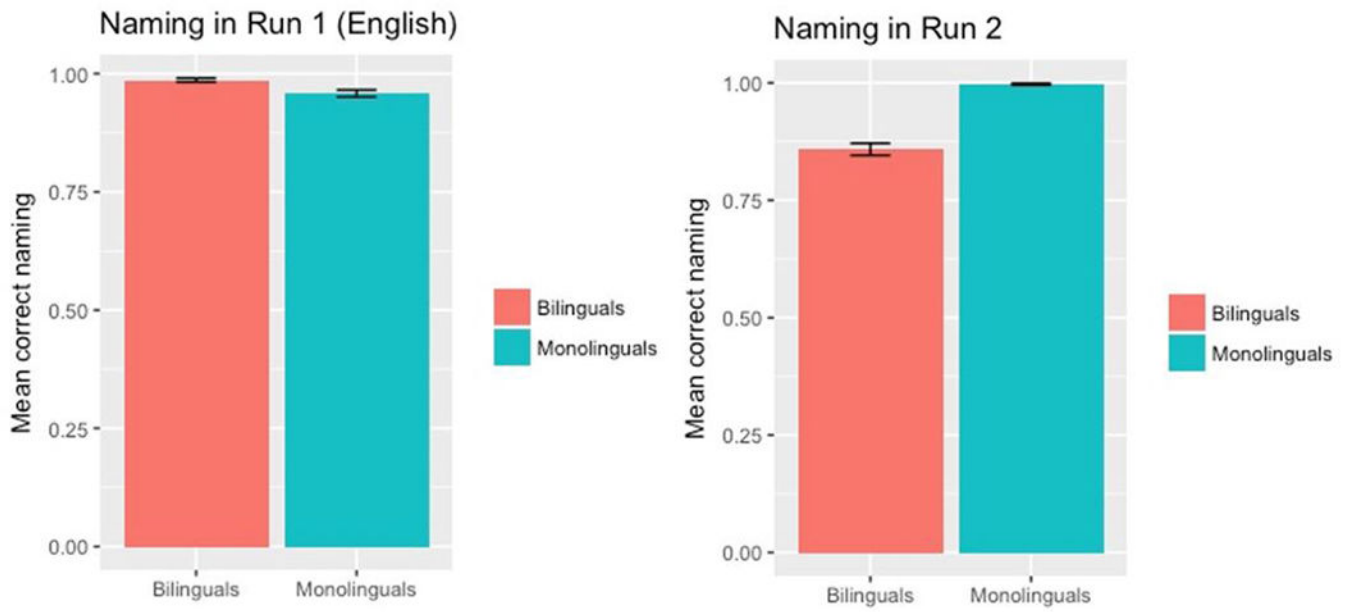
Figure 3:
Accuracy of picture naming in Runs 1 and 2 for bilinguals and monolinguals.

Figure 4:
Functional activation in Run 1 for Bilinguals > Monolinguals
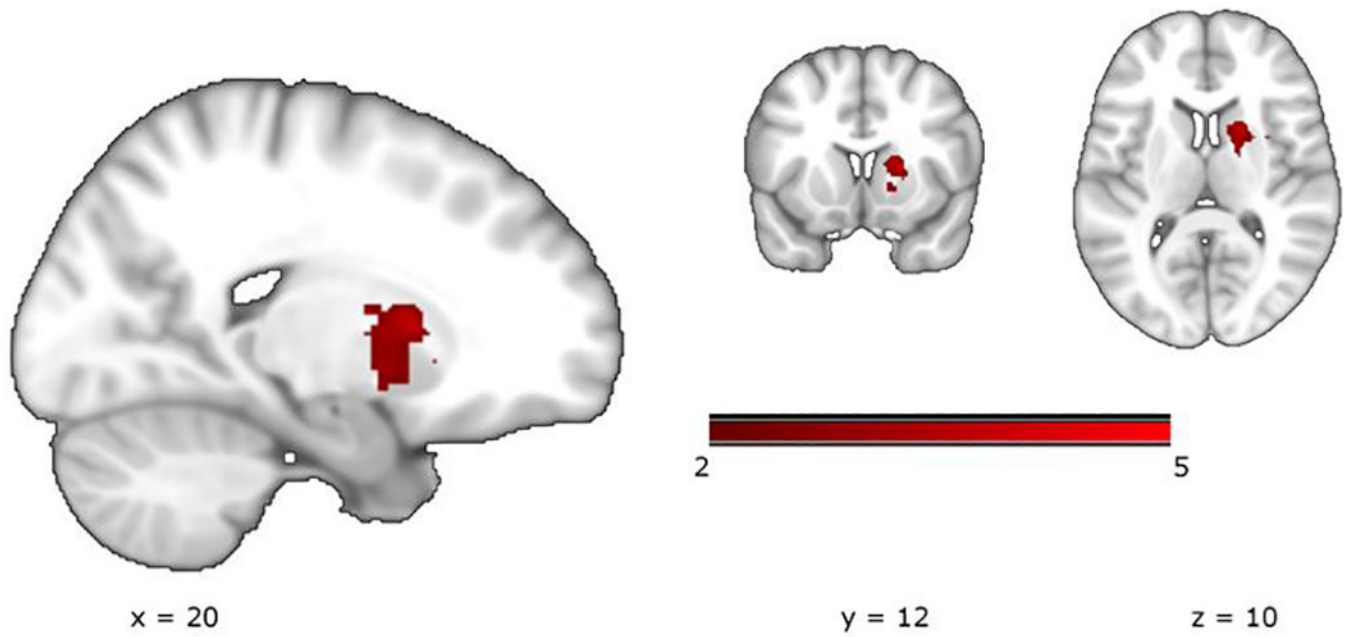
Figure 5:
Regions (right putamen) in which a significant interaction of Run × Group was found. In this region, monolinguals showed more activation during Run 1 compared to Run 2, and bilinguals elicited more activation in Run 2 (L2 naming) compared to Run 1 (L1 naming).
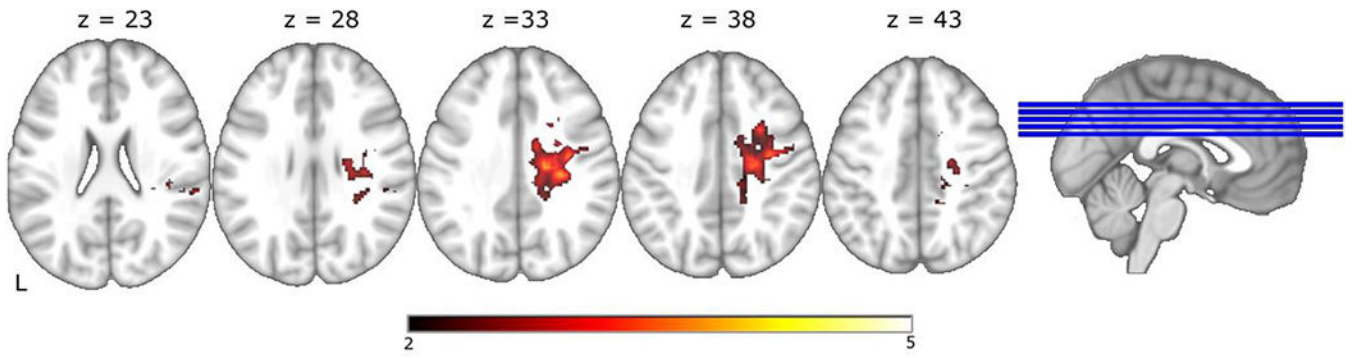
Figure 6:
Regions in which bilinguals elicited greater activation than monolinguals for items named in Runs 3–8 that were previously named in Run 1
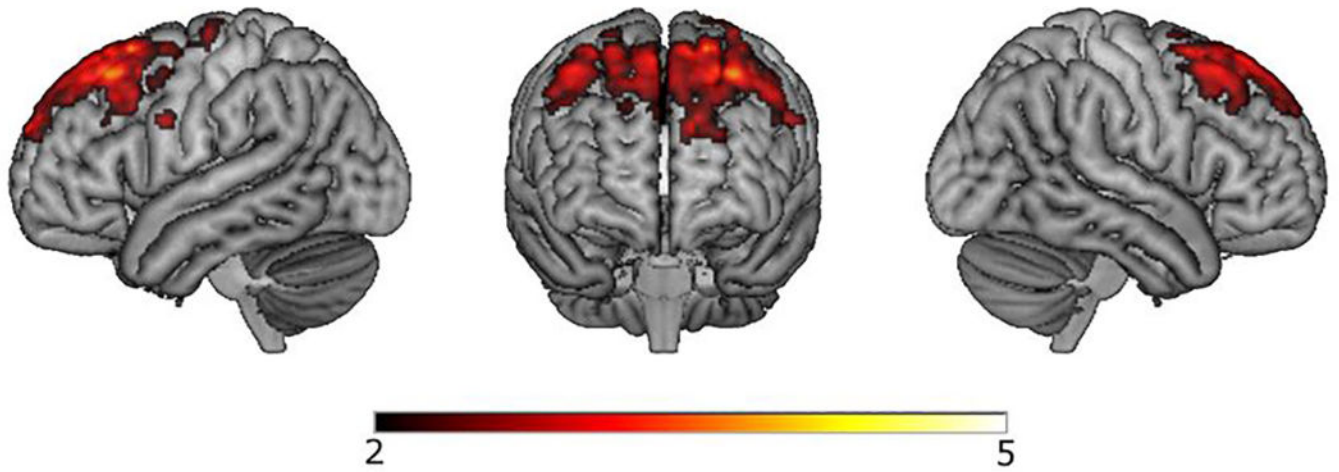
Figure 7:
Regions in which monolinguals elicited greater activation than bilinguals for items named in
Runs 3–8 that were previously named in Run 1
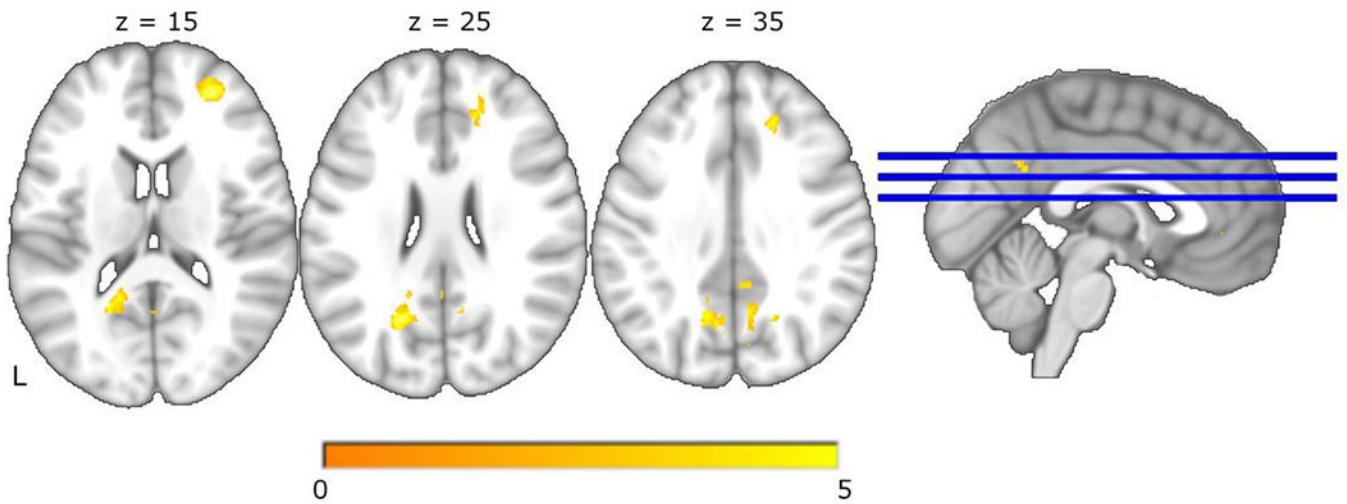
Figure 8:
Functional activation regions in which bilinguals had greater activation than monolinguals for new items from old semantic categories (previously named in English) compared to new items from new categories.
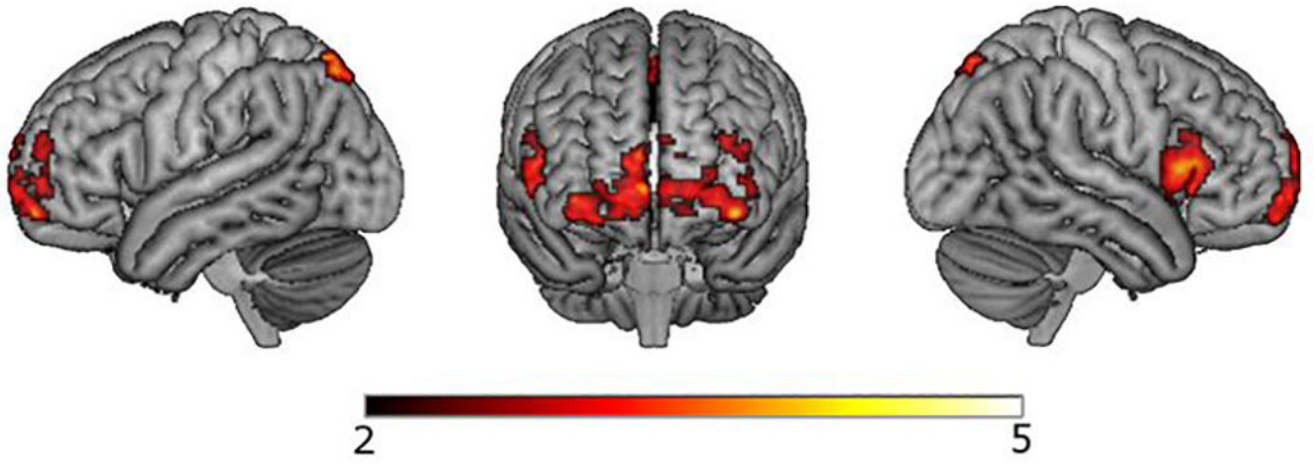
Figure 9:
Functional activation for the correlation between L2 proficiency and Run 1 activation
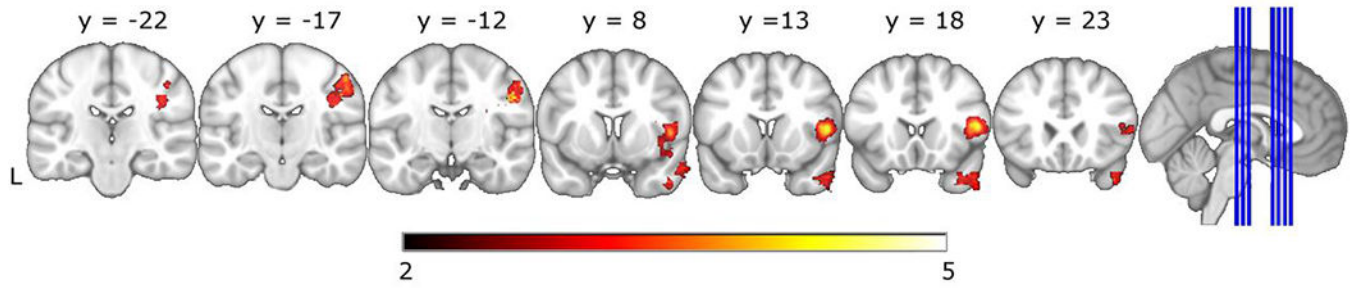
Figure 10:
Functional activation for bilinguals showing correlation of L2 proficiency and naming in Runs 3–8

Table 1:

Language measures for English-Spanish bilinguals

Participant	Self-proficiency L1	Self-proficiency L2	DELE (% score)	Composite score
1	9.25	7	0.86	1.75
2	10.00	8.75	0.74	1.76
3	9.5	10	0.72	2.81
4	10	7.2	0.48	−0.98
5	10	9	0.82	3.28
6	9.5	6.7	0.42	−1.21
7	10	7.5	0.68	1.55
8	10	5.2	0.54	−2.09
9	10	7	0.64	−1.35
10	8.75	7.4	0.58	0.21
11	10	6.2	0.62	0.42
12	10	6	0.42	−0.33
13	10	6.9	0.44	−1.24
14	10	7.1	0.52	−0.36
15	10	8.5	0.56	1.53
16	10	7.5	0.64	1.69
17	10	8	0.58	1.16
18	10	7	0.56	−0.14
19	10	6.7	0.33	−2.47
20	10	7.7	0.71	2.08
21	10	8	0.38	−1.23
22	10	8.2	0.45	−0.76
23	10	5.5	0.48	−1.78
24	10	8.7	0.68	2.2
25	10	8.5	0.58	1.41
	9.9 **(SD = 0.3)**	**7.5** **(SD = 1.1)**	**60%** **(SD = 0.1)**	**0.3** **(SD = 1.6)**

Legend: Proficiency self-ratings in both languages (1–10 Likert scale with 10 indicating the highest level of proficiency).

Table 2:

Functional activation results in run 1 for bilinguals and monolinguals

Bilinguals						
	Hemisphere	**Coordinates**			**Voxels**	**z value**
		x	**y**	**z**		
Lingual Gyrus	L	−22	−70	−4	29843	5.86
Occipital fusiform gyrus	L	−26	−72	−10		
Lingual Gyrus	R	20	−70	−4		
Putamen	R	28	−2	−2		
Insula	R	36	−18	20		
Frontal Pole	R	24	50	0	1070	3.94
Frontal Pole	R	28	46	12		
Middle Frontal Gyrus	R	32	34	34		
Cingulate	R	12	34	4		
Monolinguals						
		Coordinates			**Voxels**	**z value**
		x	**y**	**z**		
Lateral Occipital Cortex	R	44	−64	8	908	4.1
Middle frontal gyrus	L	−36	14	62	867	5.34
Putamen	L	−20	4	4	783	4.35
Putamen	R	20	4	−4	702	5.23
Thalamus	L	−6	−24	−4	630	4.07
Occipital Fusiform Gyrus	L	−32	−80	8	532	3.88

Table 3:

Functional activation results in run 1 contrasting bilinguals>monolinguals and monolinguals>bilinguals

	Hemisphere	Coordinates			voxels	z value
		x	y	z		
Run 1 Bilinguals > Monolinguals						
Precuneus	Left	−8	−44	44	8034	4.62
Precentral Gyrus	Left	−12	−28	44		
Lateral Occipital Cortex	Right	26	−60	40		
Cingulate Gyrus	Middle	−4	40	36		
Cuneal	Left	−18	−76	32		
Lateral Occipital cortex	Right	30	−78	26		
Precuneus	Middle	6	−46	46		
Superior Parietal Lobe	Left	−24	−52	48		
Postcentral Gyrus	Right	18	−32	46		
Juxtapositional Lobule Cortex	Right	10	−8	62		
Precentral Gyrus	Right	14	−26	44		
Heschl's Gyrus	Left	−32	−32	6	1316	4.01
Insular	Left	−38	−16	6		
Planum Temporale	Left	−44	−32	6		
Parietal Operculum Cortex	Left	−34	−28	20		
Central Opercular Cortex	Left	−38	−20	20		
Heschl's Gyrus	Left	−42	−28	4		
Postcentral Gyrus	Right	38	−14	30	312	3.83
Precentral Gyrus	Right	48	2	36		
Postcentral	Right	50	−14	40		
Insular	Right	34	−18	8	303	3.22
Cingulate Gyrus	Right	10	2	42	201	3.57
Paracingulate Gyrus	Right	14	8	40		
Juxtapositional Lobe	Right	10	2	50		
Juxtapositional Lobe	Left	−8	0	48	60	2.94
Precentral Gyrus	Right	28	−20	56	58	3.47
Middle Frontal Gyrus	Right	30	16	38	42	3.41
Precentral Gyrus	Left	−16	−16	54	34	2.82
Precentral Gyrus	Left	−16	−16	64		
Cingulate Gyrus	Left	−8	4	32	28	2.85
Paracingulate Gyrus	Left	−10	10	38		
Inferior Frontal Gyrus	Right	48	14	30	25	3.13
Middle Frontal Gyrus	Right	46	14	30		
Juxtapositional Lobe	Left	−6	−10	66	20	3.21
Run 1 Monolinguals > Bilinguals	No significant clusters					

Table 4:

Functional activation results for items presented in Run 3–8 that were previously named during Run 1.

	Hemisphere	Coordinates			Voxels	z value
Bilinguals > Monolinguals		x	y	z		
Precentral Gyrus	Right	30	−24	32	1879	3.29
Cingulate Gyrus	Middle	10	−14	32		
Precentral Gyrus	Right	34	−10	34		
Precentral Gyrus	Right	20	−18	32		
Precentral Gyrus	Right	26	−14	36		
Precentral Gyrus	Right	26	−10	34		
Middle Frontal Gyrus	Right	28	8	38		
Precentral Gyrus	Right	48	−6	38		
Monolinguals > Bilinguals						
Frontal Pole	Left	−12	56	40	1925	4.31
Superior Frontal Gyrus	Middle	4	56	40		
Superior Frontal Gyrus	Left	−18	30	58		
Superior Frontal Gyrus	Right	24	22	58		
Frontal Pole	Right	20	38	54		
Middle Frontal Gyrus	Right	40	20	54		
Middle Frontal Gyrus	Left	−32	26	52		
Precentral Gyrus	Left	−60	8	30	95	3.35
Middle Frontal Gyrus	Left	−56	14	34		
Inferior Frontal Gyrus	Left	−56	14	32		

Table 5:

Functional activation results showing activation for new items from old semantic categories which had previously been named in English showing greater activation than new items from new categories.

	Hemisphere	Coordinates			Voxels	z value
Bilinguals > Monolinguals		x	y	z		
Precuneus	Left	−18	−60	26	2191	3.43
Cingulate Gyrus	Middle	0	−48	26		
Supracalcarine Cortex	Left	−22	−52	16		
Frontal Pole	Right	30	48	16	801	3.53
Paracingulate Gyrus	Right	12	44	20		
Cingulate Gyrus	Middle	4	40	−2	102	2.54
Paracingulate Gyrus	Middle	2	42	−6		
Cingulate Gyrus	Right	16	42	6	16	2.31
Monolinguals > Bilinguals	No significant regions of activation					

Table 6:

Correlation between L2 proficiency and Run 1 activation for Bilinguals

	Hemisphere	Coordinates			Voxels	z value
		X	**y**	**z**		
Frontal Pole	Left	−36	60	−12	1750	4.2
Frontal Operculum Cortex	Right	46	18	6	712	4.01
Inferior Frontal Gyrus, pars opercularis	Right	56	20	10		
Temporal Pole	Right	52	16	−6		
Lateral Occipital Cortex	Left	−12	−72	54	595	5.27
Precuneus	Middle	−4	−72	54		

Table 7:

Correlation between L2 proficiency and naming in Runs 3–8

	Hemisphere	Coordinates			Voxels	z value
Correlation between L2 proficiency and Run 3 activation – Bilinguals Only		x	y	z		
Inferior Frontal Gyrus	Right	50	16	10	1099	3.7
Frontal Pole	Right	54	36	10		
Central Opercular Cortex	Right	44	4	10		
Frontal Operculum Cortex	Right	46	14	−2		
Insular	Right	42	6	−2		
Precentral Gyrus	Right	48	6	12		
Postcentral Gyrus	Right	56	−10	36	657	4.92
Supramarginal Gyrus	Right	44	−28	36		
Temporal Pole	Right	48	6	−42	495	4.37