

Two different brain networks underlying picture naming with familiar pre-existing native words and new vocabulary

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ABSTRACT

The present research used fMRI to longitudinally investigate the impact of learning new vocabulary on the activation pattern of the language control network by measuring BOLD signal changes during picture naming tasks with familiar pre-existing native words (old words) and new vocabulary. Nineteen healthy participants successfully learned new synonyms for already known Spanish words, and they performed a picture naming task using the old words and the new words immediately after learning and two weeks after learning. The results showed that naming with old words, compared to naming with newly learned words, produced activations in a cortical network involving frontal and parietal regions, whereas the opposite contrast showed activation in a broader cortical/subcortical network, including the SMA/ACC, the hippocampus, and the midbrain. These two networks are maintained two weeks after learning. These results suggest that the language control network can be separated into two functional circuits for diverse cognitive purposes.

1. Introduction

Language control denotes the cognitive processes that allow bilinguals to select a word in the target language, avoid unwanted interference from the language not in use but continuously active, and monitor their speech for potential intrusions (Abutalebi & Green, 2007; Costa, Miozzo, & Caramazza, 1999; Kroll, Bobb, & Wodniecka, 2006). The architecture of this complex system involves cortical and subcortical regions related to cognitive control (Abutalebi, 2008; Abutalebi & Green, 2007), and these regions are expected to be involved differentially depending on how well and how often a second language is used. This network includes: i) the Supplementary Motor Area/Anterior Cingulate Cortex (SMA/ACC) mediating the monitoring and suppression of conflict information (Green & Abutalebi, 2013); ii) the left prefrontal cortex (PFC) involved in response selection (Green & Abutalebi, 2013); iii) the inferior parietal lobule (IPL), responsible for maintaining representations and working memory (Green & Abutalebi, 2013); and iv) the basal ganglia (BG) associated with language selection, switching,

language planning, and lexical selection (Green & Abutalebi, 2013). In an update of the model, Abutalebi and Green (2016) elaborated a more extended neural network that includes other regions in the right hemisphere, such as the right PFC for response inhibition, the right thalamus and BG (caudate/putamen) involved in the detection of salient cues, and the cerebellum, which is linked to all the key regions of the language control network. This theory has received the support of different studies that have examined the neural mechanism used by bilinguals to manage the control of multiple languages, such as first languages (L1) of Chinese, Spanish, or German, and second languages (L2) of English, Catalan, or French (Abutalebi et al., 2013, 2008; Garbin et al., 2011; Guo et al., 2011). Furthermore, previous behavioural studies showed that bilinguals, compared to monolinguals, seemed to have a reduced speech rate (measured by picture naming latencies and articulatory durations), a greater incidence of word-finding difficulties (measured by the incidence of tip-of-the-tongue states), and slower reading times (measured by lexical decision tasks) (see Rodríguez-Fornells et al., 2005; Gollan and Brown 2006; Gollan et al., 2008, 2014; Han 2012; Palomar-García

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et al., 2015). Thus, these costs may stem from a different form of processing linguistic information in bilinguals.

Regardless of certain agreement about the neural bases of this language control network, there is some evidence showing the activation of different regions depending on what language is being used. Specifically, a recent cross-sectional study by Abou-Ghazaleh et al. (2018) examined healthy young Arabic (L1)-Hebrew (L2) early bilinguals using a picture naming task. fMRI analysis showed a greater activation of the SMA/ACC, caudate, cerebellum and right lingual gyrus when comparing naming with Hebrew words (L2) to naming with Arabic words (L1), but no differences when comparing L1 to L2. Therefore, the brain differences found are explained in terms of the engagement of the language control network. In addition, some studies revealed that the contribution of the control regions is unequal depending on the direction of the language switching (Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016; Garbin et al., 2011; Guo et al., 2011; Wang, Xue, Chen, Xue, & Dong, 2007). Specifically, Branzi et al. (2016) assessed the effects of switching between the German (L1) and Italian (L2) languages on a picture naming task. They suggest that there is a dissociation between languages in the activity in the brain regions of the language control network proposed by Abutalebi and Green (2007). Specifically, they propose that the language control network is supported by: i) the response selection system for L1, comprising the bilateral frontal and parietal regions, and ii) the supervisory attentional system for the weaker language, involving the dorsal ACC/pre-SMA.

A recent meta-analysis of functional neuroimaging research suggested a shared neural network for L1 and L2, with few differences depending on the linguistic level (Sulpizio, Del Maschio, Fedeli, & Abutalebi, 2020). Bilinguals may either directly apply the functional network of L1 in the processing of L2, or they can recruit other brain regions to accommodate the unique demands of L2 (see Abutalebi and Green 2007; Abutalebi 2008). However, it is less clear how L2 late experience or L2 lower proficiency may eventually change the functional brain network of L1. Furthermore, recent studies have proposed that cognitive control regions are more related to initial phases of L2 learning. After L2 consolidation, the activation in control areas tends to decrease (Grant, Fang, & Li, 2015; Li, Legault, & Litcofsky, 2014; Saidi et al., 2013; Yang, Gates, Molenaar, & Li, 2015).

As previous studies have reported, learning new vocabulary is a meaningful process because learners have to incorporate new words that are associated with words in their native language (L1). Studies on the neural basis of new vocabulary learning have been devoted to displaying how these words are processed in language control mechanisms, including left frontotemporal areas (Hultén, Vihla, Laine, & Salmelin, 2009; Raboyeau, Marcotte, Adrover-Roig, & Ansaldo, 2010; Raboyeau et al., 2004). Furthermore, Bradley et al. (2013) showed that only two hours of exposure to new vocabulary was related to increased activation in a set of cortical regions associated with cognitive control. However, none of these studies has directly compared the interference produced during this process and how it is resolved in the brain.

Therefore, the main goal of the present study was to longitudinally investigate the brain activation changes in the language control network during the access to new and old vocabulary immediately after learning and two weeks later. To do so, we designed a longitudinal study in which participants learned new words during different training sessions where familiar pre-existing native words (old words) were directly associated with novel vocabulary (new words). Training consisted of visual associations between a new word and a native word in Spanish. We were interested in ensuring overlearning of all the new material to obtain high and homogenous recall scores across participants at post-training. As in previous studies (Parker-Jones et al., 2012; Raboyeau, Marcotte, Adrover-Roig, & Ansaldo, 2010), we used a picture naming task that activates the whole language network. We administered the naming task three times: at baseline (only with old words), after learning, and two weeks after learning. Compared to previous studies, our study allowed us to: i) immediately after learning, investigate the effect of this

learning, not only on the new words, but also on the old words, without the switch cost that previous studies present; ii) identify the neural basis for processing new words and old words two weeks after learning; and iii) compare the processing of native words after learning new synonyms. Our hypotheses in this study were: 1) there would be different involvement of the language control regions (i.e., prefrontal cortex, parietal regions, ACC, and basal ganglia) depending on the words being used (old words or newly learned words); and 2) there would be less interference between old and new words after two weeks without training, that is, reduced activation in the language control network; and 3) processing old words after learning the new vocabulary would require stronger activation in the language system.

2. Material and methods

2.1. Participants

Participants in this study were twenty-one native Spanish speakers. Two of them were removed from the analyses because of excessive head movements (more than 2 mm of translation or 2 degrees of rotation) during one of the two fMRI acquisitions. The final sample consisted of 19 right-handed Spanish speakers (9 females, mean age = 19.9 ± 1.3 years, age range = 18–22 years old), as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). All the participants were born in the Spanish region of Valencia and resided there permanently. During a preliminary interview, they were asked about their daily use of both Spanish and Catalan and their exposure to them in a variety of contexts (i.e., home or university), as well as their personal and family language history. Next, participants filled in a questionnaire about their language history. Based on the information collected from the preliminary interview and the self-reported questionnaire, participants were considered passive bilinguals because they reported speaking only Spanish. Although they resided in the Valencian region, they did not speak Catalan but were able to understand it.

None of the participants had experienced any neurological or psychiatric disorders or had a history of head injury with loss of consciousness. All participants gave their written informed consent and received monetary compensation. This research had the approval of the Ethics Committee of the Universitat Jaume I.

2.2. Experiment overview

To obtain a longitudinal perspective, the experiment consisted of three MRI scan sessions. The baseline session took place on day 1, before the learning phase, in which participants performed the fMRI picture naming task with only old words. Session 1 (S1) took place on day 10, after six 1-hour learning sessions in which participants performed the same picture naming task as in the baseline session and another picture naming task with new vocabulary; and Session 2 (S2) was held on day 24, after a two-week period of no-training, in which participants performed the same fMRI picture naming tasks as in session 1. After S1 and S2, all the participants performed cued-recall retention tests (see Fig. 1 for an experimental overview).

2.3. Stimuli

In all, 168 Spanish words were selected from the Snodgrass and Vanderwart picture database (Snodgrass & Vanderwart, 1980). Supplementary Table I contains information about the Spanish words selected such as age of acquisition, name agreement, image agreement, familiarity, conceptual complexity in a Spanish speaking population (Alonso, Fernandez & Díez, 2015; Sanfeliu & Fernandez, 1996). New vocabulary words were created by recombining the syllables of the Spanish words, adjusting the pronunciation to fit Spanish phonology. There were no differences in syllable length between words and new vocabulary. After the new vocabulary words had been created, they

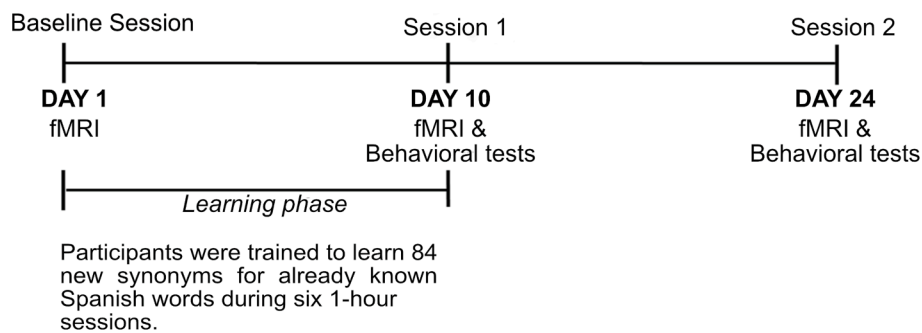


Fig. 1. Overview of the experiment.

were divided into two sets of 84 old word-new vocabulary pairs (see Supplementary Table II), counterbalancing the sets across participants. In each set, 42 pictures were employed for naming with familiar pre-existing words (old words) in the three sessions of the fMRI task, and the other 42 pictures were employed for naming with new vocabulary words in both sessions of the fMRI task.

2.4. Learning phase

Participants were taught 84 new synonyms for already known Spanish words in six 1-hour sessions that took place between day 1 and day 10 in a quiet room of our lab at Jaume I University.

Vocabulary learning was programmed using the Inquisit software (Neurobehavioral Systems, Inc., Albany, CA, USA), and it was delivered through a self-paced method that presented new vocabulary word-old word pairs. The training program included auditory and visually written presentation of 84 pairs. During the training sessions, 12 different blocks of seven new vocabulary word-old word pairs were presented, with each block repeated twice consecutively. Each new vocabulary word-old word pair appeared for approximately 500 ms. The inter-stimulus interval was 3 s, reaching a total of 21.5 s per block. At the end of each training block, a cued-recall test with feedback was given. On the test, an old word was presented visually in writing, and the participant had to recall the associated new vocabulary word. After the participant's response, the correct response was presented for 600 ms. A ten-second rest was programmed between blocks. When each training session was over, participants took a cued-recall test to evaluate their progress. On this test, the old word was presented, and the participants had to write the associated new word. No feedback was given (see Supplementary Fig. 1).

2.5. Picture-naming fMRI task

Participants carried out two different picture naming tasks, one with pre-existing naming words, and the other with new vocabulary words. The materials used in the picture naming task with pre-existing native words consisted of 42 pictures that participants had to name with old words, as well as 42 digitally distorted images, used as a control condition where participants had to say the word "noise". The picture naming task with new words consisted of 42 different pictures used to name with new words, as well as 42 digitally distorted images. The old and new vocabulary tasks were presented in a counterbalanced way across subjects. Participants were asked to produce fast, accurate responses and minimize possible head motions while overtly naming each picture and saying "noise" each time they saw distorted picture.

The experimental design for each picture naming task was an event-related where the stimuli presentation consisted of a 1 s fixation point (a black cross on a white screen), followed by the target picture (black drawings on a white screen), which stayed on the screen for 600 ms. The inter-stimulus interval (ISI) was randomized at between 3 and 7 s. An MRI-compatible microphone (FOMRITM III Fiber Optic Microphone) in

front of the participant's mouth recorded the oral responses, using a noise cancellation system. The recording started when the fixation point was presented, and it lasted 3 s. The tasks were programmed with the Presentation software (Neurobehavioral Systems, Inc., Albany, CA, USA).

2.6. fMRI parameters

The same fMRI protocol was used in the two scanning sessions. Images were acquired on a 1.5-T Siemens Avanto (Erlangen, Germany). Participants were placed in a supine position in the fMRI scanner, and fixation cushions were employed to reduce motion artifacts. FOV positioning and slice orientation were established during the first session and then automatically aligned in the following runs using the Siemens AutoAlign feature. A 3D structural MRI was acquired for each subject, using a T1-weighted magnetization-prepared rapid gradient-echo sequence (time repetition/time echo (TR/TE) = 2200/3.8 ms, matrix = 256 × 256 × 160, voxel size = 1 × 1 × 1 mm). For the fMRI tasks, 172 volumes were acquired using a gradient-echo T2*-weighted echo-planar imaging sequence (TR/TE = 2500/50 ms, matrix = 64 × 64, voxel size = 3.5 × 3.5 mm, flip angle = 90°, slice thickness = 3.6 mm, slice gap = 0.4 mm, 29 interleaved axial slices). All the scanner acquisitions were aligned to the plane intersecting the anterior and posterior commissures (AC-PC), and they covered the entire brain.

2.7. Behavioural analyses: Learning

Behavioural data were processed with the IBM SPSS Statistics software. For the learning measure, an ANOVA was performed with the eight cued-recall scores (i.e. measures obtained after the six learning sessions, and after fMRI S1 and S2) as the within-subjects factor.

The overt picture-naming responses voiced by the participants in the fMRI picture-naming task scans were recorded and analysed offline. Accuracy and naming latencies (calculated with the Praat software, <http://www.fon.hum.uva.nl/praat/>) were measured and included in a database. Next, the descriptive statistics analyses of stimuli per condition (mean accuracy and mean naming latencies) were conducted. Finally, a repeated-measures 2x2 ANOVA was conducted, with the Type of words (old words, newly learned words) and Session (Session 1, Session 2) as within-subject factor; and a repeated-measures ANOVA with the old words in the 3 sessions (baseline, Session 1, Session 2) as within-subject factor to investigate the learning effects on old words.

2.8. fMRI analysis

2.8.1. Preprocessing

Image processing and statistical analyses were carried out using SPM12 (Wellcome Trust Centre for Human Neuroimaging, London, UK). The preprocessing of the functional data involved correction of the slice timing differences for interleaved ascending acquisitions (using the middle slice in time, the 29th, as the reference slice), and realignment to

correct for possible head movements during acquisition, realigning and re-slicing the functional images to fit the mean functional image. Excessive head motion was found in two participants (more than 2 mm of translation, or 2 degrees of rotation), who were removed from further analysis. After realignment, the anatomical image was co-registered to the mean functional image, and the transformed anatomical image was segmented. During normalization to the Montreal Neurological Institute (MNI), functional images were re-sampled to 3 mm³. Finally, spatial smoothing was performed by applying an isotropic Gaussian Kernel of 6-mm full-width at a half maximum (FWHM).

2.8.2. Statistical analysis

Statistical analyses were performed in the context of the General Linear Model (Friston et al., 1995) for each participant and each time point. The blood-oxygenation level-dependent (BOLD) signal was estimated by convolving only the stimuli onset for the correct trials with the canonical hemodynamic response function (HRF). Six motion realignment parameters extracted from head motion and the performance errors were included as covariates of no interest. A high-pass filter (128 s) was applied to the functional data to eliminate low-frequency components. The first-level analyses resulted in the following contrast images per session: 1) naming with old words (old words > control condition); 2) naming with newly learned words (new words > control condition). These images were used in the following analyses.

2.8.2.1. Cross-sectional results: Learning effects on old and newly learned words. To investigate the differences between naming with old words vs. naming with newly learned words, a within-subject analysis was conducted (i.e., paired *t*-test) with the contrast obtained in the first-level analyses (naming with old words and naming with newly learned words) to evaluate the differences immediately after learning (S1) and 14 days after learning (S2).

2.8.2.2. Longitudinal results: Learning effects on old and newly learned words. To investigate the effects of learning new words on the old words, a within-subject analysis was conducted (i.e., SPM's flexible factorial analyses) with the data from naming with old words, in order to compare the different sessions (S1 with baseline session, S2 with baseline session, and S2 with S1).

To investigate long-term learning effects on new words, a within-subject analysis was conducted (i.e., SPM's flexible factorial analyses) with the data from naming with new words, to compare S2 to S1.

To investigate the longitudinal differences between naming with old vs. new words, an interaction analysis was conducted (i.e., SPM's flexible factorial analyses) with the contrast obtained in the first-level analyses (naming with old words and naming with newly learned words) to compare S2 to S1.

2.8.2.3. Threshold used in all the fMRI task analyses. To avoid false positives in the fMRI analyses (Woo, Krishnan, & Wager, 2014), the statistical criterion was set at $p < .05$, family-wise error (FWE) cluster-corrected for multiple comparisons (voxel-level uncorrected threshold of $p < .001$; cluster size appears in each result).

3. Results

3.1. Behavioural data

The training procedure was effective, as the analysis of the cued-recall test scores over time revealed (see Supplementary Fig. 1). We ran a MANOVA analysis including 8 repetitions of the cued-recall test as a dependent variable. Following the temporal order, we included the baseline, the cued-recall test after the 5 training sessions, and the cued-recall test for S1 and S2. There was a significant increase in the scores in the learning phase ($F(7,126) = 131.1$, $p < .001$), especially from day 1 to

day 4, reaching an asymptotic level. Immediately after the learning phase in S1, mean accuracy was very high, 98.3% (SD = 2.3), and it only dropped slightly two weeks later in S2, 93.9% (SD = 6.1). Then, training had short- and long-term effects on vocabulary knowledge.

With regard to the naming accuracy values during the overt picture naming task in S1 and S2 (see Fig. 2A), the results of the 2x2 ANOVA analysis yielded a significant main effect of Type of words ($F(1,18) = 17.34$; $p < .01$), and significant main effect of Session ($F(1,18) = 10.98$; $p < .01$). These main effects were driven by a significant two-way Type of words and Session interaction ($F(1,18) = 17.81$; $p < .001$). Post-hoc analyses revealed that naming pictures with old words was more accurate than naming them with newly learned words in S2, and naming pictures with newly learned words was more accurate in S1 than in S2. Finally, the results of the repeated measures ANOVA with the old words yielded a non-significant main effect of Session ($F(2,36) = 1.48$; $p > .05$).

In terms of naming latencies in S1 and S2 (see Fig. 2B), the results of the same 2×2 ANOVA yielded a significant main effect of Type of words ($F(1,18) = 385.19$; $p < .001$), indicating that participants were faster naming pictures with old words than naming them with newly learned words, as expected. No significant main effect of Session or significant interaction between the Type of words and Sessions were found. Finally, the results of the repeated-measures ANOVA with the old words yielded a significant main effect of session ($F(2,36) = 5.25$; $p = .01$), indicating that, in general, participants were faster during the baseline session than in Session 1 and Session 2.

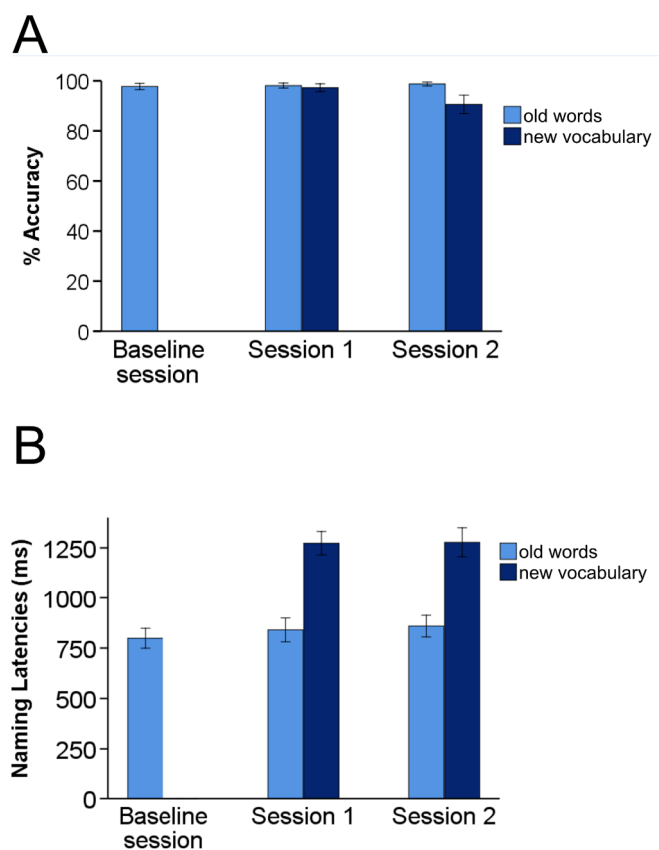


Fig. 2. Behavioural performance. A) Mean accuracy for naming with old words and new words (percentage of correct responses), and B) Mean naming latencies (in milliseconds) for naming with old words and new words in each session. Error bars represent SD.

3.2. fMRI results

3.2.1. Cross-sectional results: Learning effects on old and newly learned words.

With regard to the training effects for old words compared to newly learned words in S1, immediately after the new vocabulary was trained, activations were found in the right dorsolateral prefrontal cortex (DLPFC) and the bilateral IPL ($p < .05$ FWE cluster-corrected, voxel-wise threshold at $p < .001$, with a cluster size of 27 voxels, see Fig. 3A and supplementary Table III). The opposite contrast, newly learned words compared to old words, showed activations in the bilateral SMA, the bilateral ACC, the bilateral thalamus, the bilateral lingual gyrus, the bilateral fusiform gyrus, the bilateral posterior parahippocampal gyrus, the left premotor cortex, the right insula, and the right cerebellum ($p < .05$ FWE cluster-corrected, voxel-wise threshold at $p < .001$, with a cluster size of 27 voxels, see Fig. 3B and Supplementary Table III).

Regarding the training effects for old words compared to newly learned words in S2, after a two-week period of no-training, activations were found in the bilateral IPL, the bilateral posterior cingulate cortex (PCC), and the right DLPFC ($p < .05$ FWE cluster-corrected, voxel-wise threshold at $p < .001$, with a cluster size of 76 voxels, see Fig. 3A and supplementary Table III). The reverse contrast, newly learned words compared to old words, yielded activations in the bilateral SMA/ACC, the bilateral lingual gyrus, the left insula, and the right midbrain ($p < .05$ FWE cluster-corrected, voxel-wise threshold at $p < .001$, with a cluster size of 26 voxels, see Fig. 3B and Supplementary Table III).

3.2.2. Longitudinal results: Learning effects on old and newly learned words

When studying the immediate training effects for old words (S1 > Baseline), activations were found in the left angular gyrus/IPL, the left PCC, and the bilateral cuneus ($p < .05$ FWE cluster-corrected, voxel-wise

threshold at $p < .001$, with a cluster size of 24 voxels, see Fig. 4A and supplementary Table IV). Two weeks after learning (S2 > Baseline),

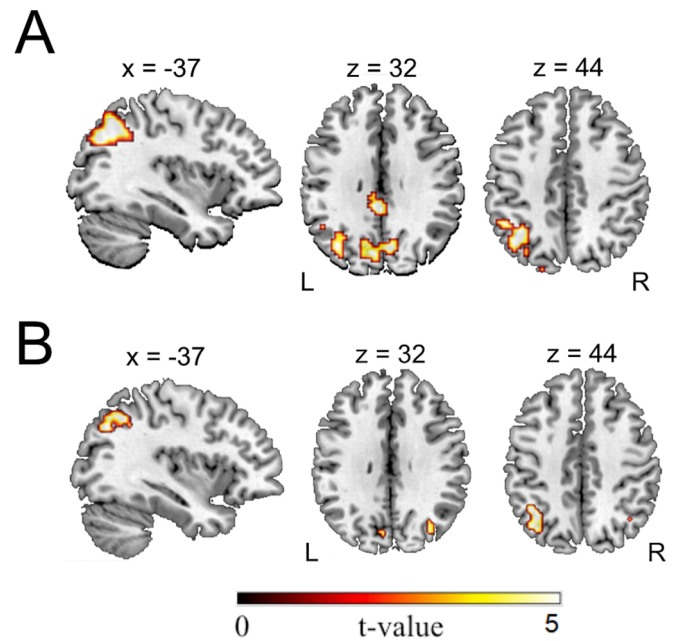


Fig. 4. Brain activations maps illustrating longitudinal results on old words: A) The immediate training effects (Session 1 > Baseline session). B) Two weeks after learning (Session 2 > Baseline session). Colour bar represent t-values. Results were $p < .05$ FWE cluster-corrected. L = Left, R = Right. Coordinates are in the MNI space.

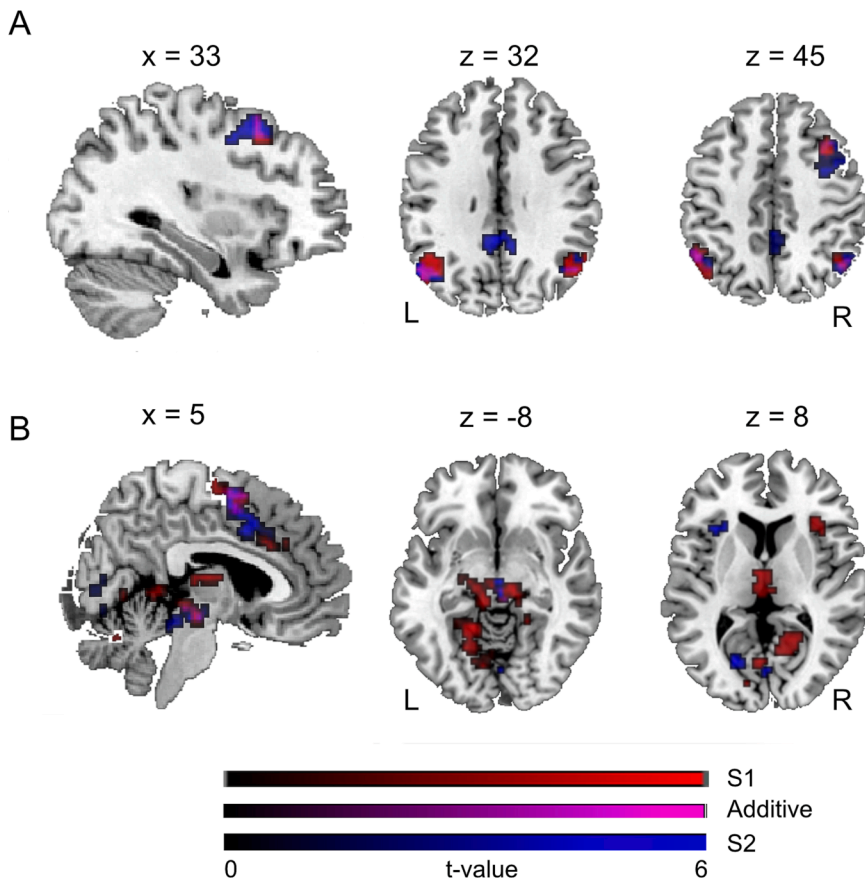


Fig. 3. Brain activation maps illustrating cross-sectional results: A) The training effects for old words compared to new words. B) The training effects for new vocabulary compared to old words. Session 1 (red), session 2 (blue), and the common regions (violet). Colour bars represent t-values. Results were $p < .05$ FWE cluster-corrected. L = Left, R = Right. Coordinates are in the MNI space. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

activations were found in the left angular gyrus/IPL, the left cuneus, and the right middle occipital gyrus ($p < .05$ FWE cluster-corrected, voxel-wise threshold at $p < .001$, with a cluster size of 21 voxels, see Fig. 4B and supplementary Table IV). The immediate effects versus the effects two weeks after learning ($S2 > S1$) yielded no significant differences.

The analysis comparing S1 and S2 while processing the new words did not yield any significant difference.

When studying the longitudinal effects, comparing the learning effects between the two conditions (old words compared to newly learned words) and comparing S2 to S1, we did not find any significant differences.

4. Discussion

Using an event-related fMRI design, the present study aimed to examine the impact of learning new vocabulary on the activation pattern of the language control network at different time points. Our results showed different activations of the language control network depending on whether participants were naming with familiar pre-existing native words (old words) or with novel word-form learning in native language (new words). Specifically, when the old words were used and the new vocabulary had to be inhibited, we found a cortical network consisting of frontal and parietal regions. In the opposite contrast, when naming was done with the weaker vocabulary and the predominant old words were inhibited, activation was found in a broader cortical network, including the SMA/ACC and subcortical regions. Thus, our study provides evidence that the language control network proposed by Abutalebi and Green (2007) could be divided into two functional circuits for different cognitive purposes.

4.1. Differences between naming with old words and naming with new vocabulary

The fMRI results showed a differential pattern depending on the words the participants were using (old words or new words). A relevant result obtained in this study focuses on the activations found when comparing the old words with the new words at different time points. Specifically, immediately after learning (S1), we found activations in two cortical areas, that is, the bilateral IPL and the right DLPFC. The IPL has previously been related to language selection (Calabria, Costa, Green, & Abutalebi, 2018; Wang, Kuhl, Chen, & Dong, 2009). Specifically, the left IPL has been proposed to bias language selection away from the language not in use, whereas the right IPL would be responsible for driving the selection towards the language in use (see Abutalebi, 2008; Abutalebi and Green, 2016). The activation of the right DLPFC has been associated with enhanced executive control functions during language switching, such as maintaining the goal of producing in the target language. Furthermore, Videsott et al. (2010) studied naming separated into blocks of different languages in multilinguals, and they reported that naming in the dominant language engages more activity in this region. Considering the main activations obtained in our study, our results for naming with old words are consistent with the results found by Branzi et al. (2016). They related the activation of these regions to the response selection system for language control, which is responsible for both engagement and disengagement of inhibitory control during language production.

In addition, our design allowed us to study the neural basis for naming with old words, compared to new vocabulary, two weeks after learning without training (S2). Activations were found in the same regions as in S1, and also in the bilateral posterior cingulate gyrus. Therefore, the processing of old words does not change the main activations after two weeks without training, and both sessions were processed with regions related to the response selection system for language control (Branzi et al., 2016). This implies that after learning the new vocabulary, you still have two different words for the same concept. Therefore, you need an efficient selection of the target stimulus, even

two weeks after learning.

Our second result explores the activations produced when naming with the new vocabulary compared to old words at different time points. Specifically, processing the newly acquired vocabulary reveals a large network of activations during picture naming in the bilateral SMA/ACC, the bilateral lingual gyrus, the bilateral fusiform gyrus, the bilateral parahippocampal gyrus, the bilateral thalamus, the left precentral gyrus, the right insula, and the right cerebellum.

First, we observed activation in brain regions related to the language control network. Specifically, we found activation in the ACC and the SMA. These regions have previously been associated with conflict information and error monitoring during language control in bilinguals (Abutalebi et al., 2012; Calabria et al., 2018). Functional activity in this region has been reported in cross-linguistic conflict resolution (Rodríguez-Fornells et al., 2005; van Heuven, Schriefers, Dijkstra, & Hagoort, 2008). Furthermore, previous studies have demonstrated that this region is more involved when processing a weaker language (Abutalebi et al., 2013; Branzi et al., 2016; Garbin et al., 2011). Indeed, we found ACC activation when the naming task was being carried out with the new vocabulary in session 1, and session 2. Within the control network, activation was also found in the right cerebellum. In production studies, cerebellar activation has been attributed to greater demands for sensorimotor integration and speech-motor articulation processes (Berken, Gracco, Chen, & Klein, 2016; Berken et al., 2015; Pillai et al., 2004; Stoodley & Schmahmann, 2010). In fact, a structural study by Filippi et al. (2011) found that grey matter density in the right cerebellum significantly predicted the ease with which bilingual speakers resisted speech interference from their first language while comprehending an utterance in their second language. Furthermore, as previous studies have reported (Fu et al., 2017; Liu, Hu, Guo, & Peng, 2010), we also found neural activation of this region when naming with new vocabulary. Specifically, we found activation in S1, but not in S2. This result is supported by Tyson et al. (2014), who related this region to the initial learning phases. Furthermore, this result could reflect the higher automaticity of the processes involved in naming with new vocabulary in S2 compared to S1. Finally, the bilateral thalamus has been shown to play a role in language and cognitive processing. Previous studies have implicated the left thalamus in object recall and lexical retrieval (Crosson et al., 2003; Kraut et al., 2002; Mestres-Missé, Càmarà, Rodríguez-Fornells, Rotte, & Münte, 2008).

Second, we observed activation in other brain regions such as the bilateral lingual gyrus, the bilateral fusiform gyrus, the bilateral parahippocampal gyrus, and the right insula. Specifically, the lingual gyrus and the fusiform gyrus have been related to controlled articulation and visual form processing (Abou-Ghazaleh et al., 2018; Hernandez, 2009; Liu et al., 2010; Ma et al., 2014). Activation of the ventral occipito-temporal cortex has been found when adults learn new lexical information (Tagarelli, Shattuck, Turkeltaub, & Ullman, 2019). Specifically, this region constitutes part of the ventral stream (“what pathway”). It has been proposed as being important in mapping sounds to meanings [Davis and Gaskell, 2009; Hickok and Poeppel, 2007; Ripollés et al., 2017; Rodríguez-Fornells et al., 2009], and it has been linked to the declarative memory system (Ullman, 2004, 2016). Previous studies have demonstrated that the hippocampal and parahippocampal gyrus have a role in the comprehension and production of meaningful speech (Awad, Warren, Scott, Turkheimer, & Wise, 2007) and listening to and reading meaningful text (Lindenberg & Scheef, 2007). Concretely, we found activation in the posterior parahippocampal gyrus, and this part has been related with subserve retrieval (Lepage et al., 1998; Mestres-Missé et al., 2008). Finally, activation was found in the right insula, which has been implicated in a number of linguistic and non-linguistic control functions (Ardila, Bernal, & Rosselli, 2014; Oh, Duerden, & Pang, 2014; Price, 2010). The activation in the anterior insula is consistent with recent research suggesting that the anterior insula serves as an “integration hub” that coordinates higher-order cognitive processes involved in speech and language processing (Oh et al., 2014).

These results indicate that more cognitive resources are required to inhibit the dominant old words and retrieve new words in a single language context when participants name pictures with new vocabulary words. As previous studies have proposed (Grant et al., 2015; Li et al., 2014; Saidi et al., 2013; Yang et al., 2015), we found less activation in the cognitive control regions after a two-week period of no-training related to initial phases of new vocabulary learning.

4.2. Learning effects on old words

Due to the learning process, changes were observed in the processing of old words after learning new vocabulary. Specifically, the immediate training effects for old words ($S1 > \text{Baseline}$) were characterized by significant activation in the left angular gyrus/ IPL, the left PCC, and the bilateral cuneus. In addition, two weeks after learning ($S2 > \text{Baseline}$), activations were observed in the same regions and also in the right middle occipital gyrus. Previous research has highlighted the role of the occipital regions in processing visual information and object recognition (Müller & Gruber, 2001). They are particularly involved in object representation and in analysing objects. These characteristics not only serve to address the mental lexicon, but they also form a part of the large-scale network that builds the semantic representation of objects [Grill-Spector et al., 2001; Huth et al., 2012]. Furthermore, the IPL has previously been related to language selection (Calabria et al., 2018; Wang et al., 2009). Specifically, when word retrieval became more semantically demanding, activation for word retrieval was reported in the left angular gyrus/IPL (Mechelli, Josephs, Lambon Ralph, McClelland, & Price, 2007; Troiani et al., 2008; Ye, Habets, Jansma, & Münte, 2011). Finally, the PCC is associated with lexical-semantic processing (Price, 2010). It has been proposed that the PCC may play a role between semantic and episodic memory (Binder, Desai, Graves, & Conant, 2009), and it has been associated with general response selection (Schulze, Zysset, Mueller, Friederici, & Koelsch, 2011). Therefore, native word processing after learning new words is modified, and it is supported by a large-scale language network that includes the left angular gyrus/IPL, the left PCC, and the visual regions.

4.3. Limitations

The present research may comprise some limitations. A first issue is that we utilized a 1.5 T scanner to collect the fMRI scans. However, currently, higher magnetic field scanners (i.e., 3, 7 T) are the gold standard, even though 1.5 T scanners are still common. The second issue is that the learning paradigm involved does not really ensure L2 type of learning. Instead, participants simply learned new Spanish synonyms for already known native words, and the task required them to access the brain regions that control the recently learned words or access the old words. The third issue is that we employed a continuous acquisition with overt speech production rather than sparse design as some previous studies recommended (Gracco, Tremblay, Pike., 2005), although a continuous acquisition is still common. Though, these methodological issues do not compromise our results, they should be considered in future research.

5. Conclusion

In summary, the cortical regions of the language control network were more engaged during naming with familiar pre-existing native words, whereas the ACC/SMA and subcortical regions were more active during naming with new vocabulary. For this reason, we can conclude that the language-control brain regions involved in the picture naming task were different depending on which words had to be produced (old words or new words). In other words, at least in people who are learning new vocabulary with different words that are not equally balanced in terms of dominance and use, the language-control brain network is involved to a different extent depending on whether the word to be

produced is an old or newly learned word.

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7. Informed Consentxxx

Informed consent was obtained from all adult participants included in the study.

8. Ethics Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional Review Board of the Universitat Jaume I and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

CRediT authorship contribution statement

María-Ángeles Palomar-García: Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Esteban Villar-Rodríguez:** Formal analysis, Writing – review & editing. **Cristina Pérez-Lozano:** Formal analysis, Writing – review & editing. **Ana Sanjuán:** Conceptualization, Funding acquisition, Writing – review & editing. **Elisenda Bueichekú:** Methodology, Writing – review & editing. **Anna Miró-Padilla:** Methodology, Writing – review & editing. **Victor Costumero:** Methodology, Software, Writing – review & editing. **Jesús Adrián-Ventura:** Methodology, Software, Writing – review & editing. **María-Antonia Parcet:** Methodology, Writing – review & editing. **César Ávila:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bandl.2023.105231>.

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